Mechanical Systems and Signal Processing 40 (2013) 385–399

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Parameter estimation from wave propagation tests on a tube perforated by helical slots ☆

Hans Norlander [a,*], Urmas Valdek [b], Bengt Lundberg [b], Torsten Söderström [a]

[a] Department of Information Technology, Uppsala University, P O Box 337, SE-75105 Uppsala, Sweden
[b] Department of Engineering Sciences, Uppsala University, P O Box 534, SE-75121 Uppsala, Sweden

ARTICLE INFO

Article history:
Received 17 September 2012
Received in revised form
29 January 2013
Accepted 21 April 2013
Available online 21 May 2013

Keywords:
Tube
Helical slots
Elastic wave
Extension
Torsion
Parameter estimation

ABSTRACT

For a tube with doubly symmetric cross section and perforations by helical slots there is a coupling between extension and torsion. In this paper a one dimensional (1D) model structure for a tube with such a helical slot segment (HSS) is established, and parameters accounting for the coupling between extension and torsion are estimated from wave propagation experiments. In these experiments incident extensional waves were generated through axial impact by strikers of different lengths, causing reflected and transmitted waves of extensional and torsional type which were measured in terms of surface strains on either side of the HSS part of the tube. A statistical test on the experimental data shows that the output residuals (the difference between modeled and experimental output) cannot be explained by measurement noise alone. This is not surprising since the 1D model structure is based on some simplifying assumptions concerning the geometry of the HSS. Parameters for two different geometries of the HSS are estimated, and the models are assessed in terms of model fit, simulations and wave energy distribution. It turns out that for one case, where the geometrical assumptions are valid, the 1D model is adequate, while for another case, where the validity of the assumptions is questionable, it is not. It is concluded that the 1D model structure provides a simple and efficient description of the HSS if the geometrical assumptions are valid.

1. Introduction

A straight rod is said to be pre-twisted if in its stress-free state the angular orientation of its cross section varies axially. Structural elements describable as pre-twisted rods are used as blades of propellers, turbines and fans, and as screws, drill tools, cables, ropes, etc. Because of their complex behavior and engineering importance, such structural elements have been subjected to numerous studies during the last fifty years. A comprehensive review of work published before 1991 was provided by Rosen [24].

For a rod with doubly symmetric cross section, pre-twist introduces coupling between extension and torsion, but not between these modes and bending. Thus, when a pre-twisted rod is compressed it tends to twist, and when it is extended it tends to untwist. Inversely, when such a rod is twisted it tends to contract, and when it is untwisted it tends to extend.

☆ This research was partially supported by the Swedish Research Council, Contract 621-2007-6364.

* Corresponding author. Tel.: +46 184713070; fax: +46 18511925.
E-mail addresses: Hans.Norlander@it.uu.se (H. Norlander), Urmas.Valdek@angstrom.uu.se (U. Valdek), Bengt.Lundberg@angstrom.uu.se (B. Lundberg), Torsten.Soderstrom@it.uu.se (T. Söderström).

0888-3270/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ymssp.2013.04.011

In dynamics, the coupling of extensional and torsional motions generates modes of vibrations and waves that can often be described as predominantly either extensional or torsional.

This paper deals with the reflection and transmission of elastic waves in a tube containing a segment perforated by an even number of helical slots uniformly distributed around the tube wall. In such a helical slot segment (HSS), the cross sections are doubly symmetric and therefore it is assumed that there is coupling between extension and torsion only. Based on this assumption a one dimensional (1D) model of the HSS is established. The reflected and transmitted waves of both extensional and torsional type generated by an incident extensional wave are studied by use of Fourier transformation. Parameters accounting for the coupling between extensional and torsional waves are estimated from wave propagation experiments. These experiments were performed for HSSs with two different geometries, and for incident waves generated through axial impact by strikers of different lengths. The validity of the 1D model description is assessed for in terms of model fit and simulations. Attention is also paid to the energies carried by the reflected and transmitted waves of both types. The energies carried by these waves, originating from incident waves generated by strikers of different lengths, are determined by use of the estimated models and are compared with the corresponding energies obtained experimentally.

The objective of this study is to obtain parameters for a 1D model of an HSS from wave propagation experiments, and to investigate the validity of this 1D model with respect to the geometry of the HSS. The parameters are obtained by estimation using techniques common in system identification, of which a comprehensive description is found in, e.g., Ljung [11] and Söderström and Stoica [27]. The motivation for a 1D model, rather than a 3D model, is its simplicity and its transparency to the underlying physics. An alternative approach would be to calibrate a 1D model by aid of FEM simulations.

The estimation procedure used in this study, minimization of a cost function, gives rise to a separable nonlinear least squares (NLS) problem. Such problems have been used, e.g., for determining material parameters of viscoelastic materials, see Söderström and Rensfelt [26], Mossberg et al. [14] and Mahata et al. [12,13]. The cost function is also used for evaluation of the model fit, which is used assessing the validity of the estimated 1D models. This model validation is of particular interest since the 1D model structure is taken to be valid only for certain geometries of the HSS.

Although the main motivation for the study is interest in the basic phenomena involved, there are also potential applications. For example, the partial conversion of extensional waves into torsional waves by an HSS device may admit generation of combined loads in wave-based methods for drilling and materials testing.

Pioneering studies of pre-twisted rods were conducted by Chu [3], who studied the influence of pre-twist on torsional stiffness, by Okubo [15–17], who used 3D linear theory of elasticity for studies of torsion and extension of pre-twisted rods, and by Knowles and Reissner [9], who studied the coupling between extension and torsion in pre-twisted thin rods by use of shell theory. Rosen [23] accounted for warping in the analysis of pre-twisted rods, Durocher and Kane [5] developed an approximate stiffness matrix for a twisted beam element, and Krenk [10] derived an asymptotic formula based on 3D linear elasticity for the untwist of a pre-twisted rod subjected to extension.

Early studies of natural frequencies associated with coupled extensional and torsional vibration of thin pre-twisted rods were carried out by Di Prima [4], who found that pre-twist significantly increases the natural frequencies of modes that are predominantly torsional. At about the same time Carnegie [1,2] studied torsional vibrations of a pre-twisted cantilever rod and obtained good agreement between theoretical and experimental results.

Recently, Stephen and Zhang [28] extended Di Prima's approach for a study of coupled extension-torsion vibrations of repetitive beam-like structures, and Roukema and Altintas [25] studied torsional-axial chatter vibrations in a drill. Waves in pre-twisted rods have also been studied recently. In such studies, Onipede [18] and Onipede et al. [20,19] used FEM. Ergashov [6] studied the propagation of elastic waves in wound structures such as ropes, cables and yarns, and Raoof et al. [21] investigated the response of axially preloaded spiral strands to impact loading.

The paper is organized as follows. In Section 2 a 1D model structure for the HSS is established, and the relation between the extensional and torsional waves in the HSS and the measured strains is derived. A statistical test of the model structure and the experimental conditions is introduced in Section 3, and in Section 4 the parameter estimation procedure is presented. In Section 5 the experimental set-up and procedure are described. Section 6 presents the results from the statistical test on the experimental data as well as the estimated model parameters. Assessments of the validity of the estimated models are discussed in terms of model fit, simulations and the energy distribution over the different types of waves. Finally, some concluding remarks are given in Section 7.

2. Modeling

Consider a straight tube with inner radius a and outer radius b as depicted in Fig. 1. The perimeter is $L=2\pi b$, the cross sectional area is $A=\pi(b^2-a^2)$ and the polar second moment of area is $J=\pi(b^4-a^4)/2$. The tube consists of semi-infinite input and output segments separated by an HSS. The latter is perforated by four identical helical slots with angular separation $\pi/2$ and uniform counter-clockwise pre-twist. Fig. 2 shows the HSS unfolded. The helical slots have pitch p, and occupy a sector of angular width β. The pitch is defined as the axial length corresponding to a full turn, see Fig. 2. Within the HSS, due to the slots, the cross sectional area is $A_0=(1-4\beta/360^\circ)A$ and the polar second moment of area is $J_0=(1-4\beta/360^\circ)J$ (with β in degrees). The material of the tube is isotropic and linearly elastic with Young's modulus E, Poisson's ratio ν and density ρ. The shear modulus is $G=E/2(1+\nu)$.

In what follows a model relating extensional and torsional waves in the tube and measured surface strains is established. Entities associated with extensional waves are indicated by the subscript e, and those associated with torsional waves are