Emerging Design Solutions in Structural Health Monitoring Systems

Diego Alexander Tibaduiza Burgos
Universidad Santo Tomás, Colombia

Luis Eduardo Mujica
Universitat Politecnica de Catalunya, Spain

Jose Rodellar
Universitat Politecnica de Catalunya, Spain

A volume in the Advances in Civil and Industrial Engineering (ACIE) Book Series

ENGINEERING SCIENCE REFERENCE
An Imprint of IGI Global

Published in the United States of America by
Engineering Science Reference (an imprint of IGI Global)
701 E. Chocolate Avenue
Hershey PA, USA 17033
Tel: 717-533-8845
Fax: 717-533-8661
E-mail: cust@igi-global.com
Web site: http://www.igi-global.com

Library of Congress Cataloging-in-Publication Data

Emerging design solutions in structural health monitoring systems / Diego Alexander Tibaduiza Burgos, Luis Eduardo Mujica, and Jos? Rodellar, editors.
pages cm
Includes bibliographical references and index.
ISBN 978-1-4666-8490-4 (hardcover) -- ISBN 978-1-4666-8491-1 (ebook) 1. Structural health monitoring. 2. Artificial intelligence--Engineering applications. 3. Structural analysis (Engineering) 4. Structural design. I. Tibaduiza Burgos, Diego Alexander, 1980- editor. II. Mujica, Luis Eduardo, 1976- editor. III. Rodellar, Jos?, editor.
TA656.6.E44 2015
624.1'71--dc23
2015010307

This book is published in the IGI Global book series Advances in Civil and Industrial Engineering (ACIE) (ISSN: 2326-6139; eISSN: 2326-6155)

British Cataloguing in Publication Data
A Cataloguing in Publication record for this book is available from the British Library.

All work contributed to this book is new, previously-unpublished material. The views expressed in this book are those of the authors, but not necessarily of the publisher.

For electronic access to this publication, please contact: eresources@igi-global.com.

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ISSN: 2326-6139
EISSN: 2326-6155

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Nonlinear Ultrasonics for Early Damage Detection

Rafael Munoz
Universidad de Granada, Spain

Juan Chiachío Ruano
Universidad de Granada, Spain

Guillermo Rus
Universidad de Granada, Spain

Manuel Chiachío
Universidad de Granada, Spain

Nicolas Bochud
Universidad de Granada, Spain

Sergio Cantero
Universidad de Granada, Spain

Daniel J. Barnard
Iowa State University, USA

Antonio M. Callejas
Universidad de Granada, Spain

Juan Melchor
Universidad de Granada, Spain

Laura M. Peralta
Universidad de Granada, Spain

Leonard J. Bond
Iowa State University, USA

ABSTRACT

Structural Health Monitoring (SHM) is an emerging discipline that aims at improving the management of the life cycle of industrial components. The scope of this chapter is to present the integration of nonlinear ultrasonics with the Bayesian inverse problem as an appropriate tool to estimate the updated health state of a component taking into account the associated uncertainties. This updated information can be further used by prognostics algorithms to estimate the future damage stages. Nonlinear ultrasonics allows an early detection of damage moving forward the achievement of reliable predictions, while the inverse problem emerges as a rigorous method to extract the slight signature of early damage inside the experimental signals using theoretical models. The Bayesian version of the inverse problem allows measuring the underlying uncertainties, improving the prediction process. This chapter presents the fundamentals of nonlinear ultrasonics, their practical application for SHM, and the Bayesian inverse problem as a method to unveil damage and manage uncertainty.

DOI: 10.4018/978-1-4666-8490-4.ch009

INTRODUCTION

Nonlinear ultrasonics can play a major role in industrial structural health monitoring, since one of its main features is the capability to detect early damage manifestations. The nonlinear constitutive properties of a material, in the sense of deviation from Hooke's law, are recently being shown to be orders of magnitude more sensitive to micro-damage than the linear ones. As a consequence, a number of effects arise in the propagation of the ultrasonic waves as they interact with the material nonlinearity (Ostrovsky & Johnson, 2001; Broda, Staszewski, Martowicz, & Silberschmidt, 2014), namely,

- **Higher Harmonics Generation:** When a sinusoidal wave is emitted, a signal with additional harmonics, multiples of the fundamental, is received.
- Hysteretic mechanical behavior, in the stress-strain relationship.
- Wave modulations:
  - In amplitude and phase when two sinusoidal frequencies are propagated.
  - **Cross-Modulation of Waves (Luxemburg-Gorky Effect):** Passing modulation from an amplitude modulated excitation to a simultaneous and initially pure sinusoidal excitation.
- Amplitude dependent resonant frequency shifts when the material is insonified.
- Attenuation that depends on the excitation amplitude.
- **Acoustic Conditioning:** An immediate offset on material property values when insonification is active. The initial transient period time is also referred as fast dynamics.
- **Relaxation Effects or Fast and Slow Dynamics:** When excitation vanishes, material properties has a partial fast recovery and a slow final recovery that last minutes to achieve the original values, before excitation.
- Subharmonic generation.

These nonlinear effects, which are originated in the materials' microscopic and mesoscopic structures, are separable from the linear propagation in the frequency domain by a variety of experimental configurations (Ostrovsky & Johnson, 2001; Zheng, Maev, & Solodov, 1999; Jhang, 2009). Mesoscopic size is the scale of early damage manifestations, and micro-damage has also been shown to be particularly invisible to linear techniques (Nicholson & Bouxsein, 2000). Some recent experimental observations suggest that hysteretic and/or *nonlinear mechanical properties* may be a key factor to quantify changes and could unveil details of the micro- and meso-structure; both the intrinsic nonlinearity in the material or that of an induced damage. In practice, micro-damage modes such as micro-cracks behave as ultrasonic sources at frequencies different from the excitation, making it a promising tool to clearly locate and quantify damage (Matikas T., 2010). Nonetheless, few studies have been performed on the relationship between crack density and level of nonlinearity (Haupert, et al., 2014; Renaud, Callé, Remenieras, & Defontaine, 2008).

Industry will always quest for an as early as possible detection of damage. The increasing complexity of materials and damage modes, along with early detection needs, is leading to a cutting-edge development and usage of nondestructive techniques. The challenge is the extraction of a weak damage signature within the received signals. This demanding evaluation of the material integrity is one of the drivers on the incorporation of theoretical models to discriminate these weak damage signatures, by means of solving a model-based inverse problem. The aim is to reproduce, by modeled simulations, the acquired signals of the test, using an iterative procedure, which progressively adjusts the values of the model parameters,