Journal of Sound and Vibration ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Full-field, high-spatial-resolution detection of local structural damage from low-resolution random strain field measurements

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ARTICLE INFO

Article history:
Received 6 February 2016
Received in revised form
27 February 2017
Accepted 16 March 2017
Handling Editor: I. Trendafilova

Keywords:
Damage detection
strain field
incomplete measurements
high resolution
convex optimization
singular value decomposition

ABSTRACT

Structural damage is typically a local phenomenon that initiates and propagates within a limited area. As such high spatial resolution measurement and monitoring is often needed for accurate damage detection. This requires either significantly increased costs from denser sensor deployment in the case of global simultaneous/parallel measurements, or increased measurement time and labor in the case of global sequential measurements. This study explores the feasibility of an alternative approach to this problem: a computational solution in which a limited set of randomly positioned, low-resolution global strain measurements are used to reconstruct the full-field, high-spatial-resolution, two-dimensional (2D) strain field and rapidly detect local damage. The proposed approach exploits the implicit low-rank and sparse data structure of the 2D strain field: it is highly correlated without many edges and hence has a low-rank structure, unless damage—manifesting itself as sparse local irregularity—is present and alters such a low-rank structure slightly. Therefore, reconstruction of the full-field, high-spatial-resolution strain field from a limited set of randomly positioned low-resolution global measurements is modeled as a low-rank matrix completion framework and damage detection as a sparse decomposition formulation, enabled by emerging convex optimization techniques. Numerical simulations on a plate structure are conducted for validation. The results are discussed and a practical iterative global/local procedure is recommended. This new computational approach should enable the efficient detection of local damage using limited sets of strain measurements.

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1. Introduction

Structures in civil, mechanical, and aerospace engineering undergo aging and deterioration during their service life due to normal operational loads and environmental effects, as well as extreme events such as collisions, blasts, natural hazards, etc. They become increasingly vulnerable to fatigue cracks, corrosion, and impact damage. Structural health monitoring

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http://dx.doi.org/10.1016/j.jsv.2017.03.016
0022-460X/Published by Elsevier Ltd.

(SHM) technology with a sensing system and a suite of data processing algorithms provides a means to assess structural condition and detect structural damage in real time, which facilitates immediate warning of structural failure and timely maintenance.

Damage is typically a local phenomenon [1] that initiates and propagates from a limited area, so full-field global structural measurement with high spatial resolution is often required to detect small isolated regions of local damage. Since strain directly relates to damage initiation and development, high-spatial-resolution strain measurement is critical to detect damage. Existing strain sensors include traditional resistance strain gauges and Fiber Bragg grating (FBG) sensors [2], which measure strain at discrete positions in specific directions. Other types of advanced strain technologies have also been successfully employed in SHM applications, including piezoelectric strain sensors [3], MEMS strain sensors [4], and carbon nanotube-based strain sensors or "sensing skin" [5,6]. For more thorough, high-resolution, damage detection using these discrete- and contact-type sensors, one can obtain improved spatial resolution by decreasing the distance between strain sensors. This obviously requires a denser simultaneous/parallel deployment of sensors over the area of interest, entailing higher costs and the possibility of more interference with the structure's performance.

More recently distributed optical fiber sensing (DOFS) technology has shown great promise to achieve higher spatial resolution strain measurements in SHM applications [7]. Dependent on the interaction mechanism between the propagating light and the optical fiber on different spectral bands - Raman, Brillouin, and Rayleigh backscattering, various DOFS techniques have been developed and widely studied in SHM (e.g., a comprehensive review [8]). Among them, the Rayleigh backscattering based Optical Backscattered Reflectometers (OBR) can achieve strain measurement at a very high spatial resolution [7–10] on the level of 1 mm. As they also require contact with the structure (embedded or bonded) during strain measurements, significant challenges exist in SHM field applications due to the fragility of the fibers.

As a non-contact optical technique, digital image correlation (DIC) [11], has shown promise for full-field, high-spatial-resolution strain measurements; it is less practical for wide-range SHM applications, however. Recently, an alternative non-contact optical strain measurement method has been developed based on the spectral properties of single-walled carbon nanotubes [12–14]. In this method, the nanotubes are embedded in a polymeric film applied to a structural substrate as a "strain paint" or "strain-sensing smart skin." When irradiated by the laser, strain in the substrate is transmitted to the nanotubes and measured at any desired position and direction by recording systematic wavelength shifts in the nanotube near-infrared fluorescence spectra. Analogous to simultaneous/parallel discrete strain sensor (array) measurements where high spatial resolution requires denser sensor deployment, for sequential, point-by-point scanning measurement methods such as using "strain paint", higher spatial resolution also requires a denser grid of single-point sequential measurements and thus increased time for data acquisition and analysis.

An alternative to denser sensor deployment (enhanced hardware) for achieving higher spatial resolution is through a computational model, such as a finite element model (FEM) of the structure, to predict the full-field strain from a limited set of measurements. Variational principle [15,16] and modal expansion methods [17–19] performing on the FEM have been derived and used for plate and beam structures. In many cases, however, an accurate FEM may not be available.

This study presents a purely computational approach, without using an FEM, for reconstructing a full-field, high-spatial-resolution strain field and automating the detection of local damage using only a limited number of global strain measurements measured with low spatial resolution. The proposed approach exploits the implicit data structure of the 2-dimensional (2D) strain field measurement and formulates it as a matrix completion and decomposition problem, which is solved by the emerging convex optimization techniques [20–26]. It is shown that the proposed method enables automated full-field, high-spatial-resolution detection of local damage using limited, randomly positioned global strain measurements. It provides a new computational alternative that could be used for damage detection based on strain data from limited discrete positions.

2. Problem statement

Suppose one is monitoring the health state to detect possible damage of a structure (e.g., a plate) through strain measurements on a regular grid pattern with a fine enough resolution, as shown in Fig. 1; wherein, each grid point denotes a

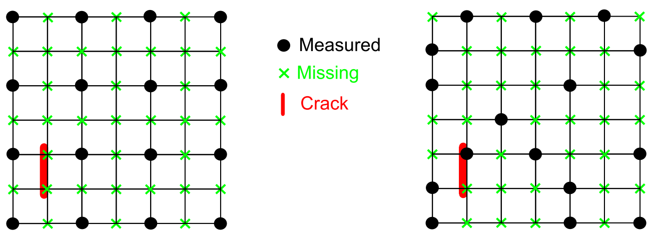

Fig. 1. (a) (Left) The uniform under-measuring method using a limited set of uniformly positioned measurements. (b) (Right) The random under-measuring method using a limited set of randomly positioned measurements. The rectangular grid (candidate measurement positions) denotes the desirable resolution of strain measurements. The black solid circles and the green "x" denote the available and missing strain measurements, respectively.