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Compressive sensing approaches for condition monitoring and Laser-scanning based damage visualization

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Abstract

Condition monitoring (CM) and Non-destructive testing (NDT) encounter a big data problem because they require to continuously measure vibration or wave data with a high sampling rate. In this study, compressive-sensing approaches for both condition monitoring and non-destructive testing are proposed to efficiently handle a huge amount of data and to improve the damage-detection capability of the current process. Compressive sensing is a novel sensing/sampling paradigm that takes much fewer samples compared to traditional sampling methods. For CM experiments, a built-in rotating system was used, and all data were compressively sampled to obtain compressed data. Optimal signal features were then extracted without the reconstruction process and were used to detect and classify damage. Also Non-destructive testing was conducted by using compressed scanning with a Laser Doppler Vibrometer (LDV) system equipped with a mirror tilting device. Wave fields were obtained by scanning through a random and compressive pattern in the spatial domain and full wave fields were reconstructed from the compressively measured data. The damage region was then identified and visualized using wavenumber based signal processing. Experimental results showed that the proposed method could effectively improve the data-processing speed and the detection accuracy of condition monitoring and non-destructive testing.

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Keywords: Compressive Snesing, Condition monitoring, Nondestructive testing, laser doppler vibrometer, damage detection

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1. Introduction

Structural Health Monitoring (SHM) and Non-Destructive Testing (NDT) identifies structural defects before it reaches a critical state, using various sensing devices and signal processing methods [1]. Tremendous research efforts are dedicated to these areas. When applying these techniques to engineering structures such as bridge, building, aircraft or ship, a large number of sensors are usually required. Moreover, continuous measurements with a high sampling frequency should be carried out for accurate diagnosis. However, such measuring strategies cause certain problems, including time and energy consumption for transferring and handling a large amount of data [2].

In order to overcome the big data problems, compressive sensing has been recently proposed [7]. Compressive sensing refers to measuring and recovering a signal whose length is much shorter than that of the original signal. Because of this advantage, compressive sensing techniques have been widely used in areas of electrical, electronic and telecommunications [8, 9, 10]. Although studies on compressive sensing approach for SHM, NDT and CM are in an initial state, several studies are reported. Höglund et al. [11] performed a damage detection study for bridges by recovering the compressive-sensing data. Bao et al. [12] simulated the process of compressive sensing by applying a mathematical model and demonstrated the efficiency of compressive sensing. Ji et al. [13] reconstructed compressive measurements using OMP algorithm and analyzed the performance of signal reconstruction with various compressive ratios. Mascarenas et al. [14] proposed a compressive sensing technique using a Gaussian random matrix for damage detection of a three story structure. In the study, compressed signals were reconstructed using L1 minimization method and used for damages detection. Yang and Nagarajaiah [15] localized and estimated the severity of damage through a compressive sensing technique using blind feature extraction. Mensil et al. [16] proposed a method to reconstruct a guided wave signal from compressive measurements and demonstrated the performance.

Currently research to compressive sensing applications in SHM, NDT or CM is performed only using the reconstructed signals rather than directly using compressed data. In this study, condition monitoring of a rotating machinery system and a laser scanning based damage visualization using compressive sensing were conducted. For the condition monitoring, a built in rotating machinery system was used. Various damage-sensitive features were extracted from compressed data without the reconstruction process. Early damage detection and fault diagnosis were then implemented using the statistical analysis, which demonstrates the applicability of compressive sensing to CM. For structural damage detection, a Laser Doppler Vibrometer (LDV) with a mirror tilting device was used. In the experiments, an actuator was attached on the surface of a structure to excite at a single frequency. Wave field signals were randomly and compressively measured in the spatial domain and the full wave field is reconstructed. A wavenumber based signal processing was then implemented to visualize and evaluate damage. Additionally, the performances of damage visualization with various compression ratios were compared in order to investigate the optimal compression ratio.

2. Theory of Compressive Sensing

The current signal measurements of data acquisition devices are based on the Nyquist sampling theory, which indicates that the sample rates are at least twice the signal bandwidths in order to preserve all the information in the signals. Data for condition monitoring applications is generally collected using a distributed sensor network with a high sampling frequency, which may introduce several problems such as a large amount of data and a lack of storage space, as well as increase in the signal processing time.

In 2006, Donoho [7] proposed compressive sensing that could recover signals without measuring the signals above a certain level in the Nyquist sampling frequency. The theory of compressive sensing states that sampling rates depend on the information on the sparsity of signals. Natural signals are normally not sparse by themselves. However, they are typically sparse when expressing in a basis Ψ.

$$s=\Psi^{-1}x \tag{1}$$

Where $x \in \mathbf{R}^n$ is the signal in the temporal domain, and $\Psi \in \mathbf{R}^{n \times n}$ is the inverse of an orthogonal basis. The