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Harnessing data structure for recovery of randomly missing structural vibration responses time history: Sparse representation versus low-rank structure

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ABSTRACT

Randomly missing data of structural vibration responses time history often occurs in structural dynamics and health monitoring. For example, structural vibration responses are often corrupted by outliers or erroneous measurements due to sensor malfunction; in wireless sensing platforms, data loss during wireless communication is a common issue. Besides, to alleviate the wireless data sampling or communication burden, certain accounts of data are often discarded during sampling or before transmission. In these and other applications, recovery of the randomly missing structural vibration responses from the available, incomplete data, is essential for system identification and structural health monitoring; it is an ill-posed inverse problem, however.

This paper explicitly harnesses the data structure itself—of the structural vibration responses—to address this (inverse) problem. What is relevant is an empirical, but often practically true, observation, that is, typically there are only few modes active in the structural vibration responses; hence a sparse representation (in frequency domain) of the single-channel data vector, or, a low-rank structure (by singular value decomposition) of the multi-channel data matrix. Exploiting such prior knowledge of data structure (intra-channel sparse or inter-channel low-rank), the new theories of ℓ_1-minimization sparse recovery and nuclear-norm-minimization low-rank matrix completion enable recovery of the randomly missing or corrupted structural vibration response data. The performance of these two alternatives, in terms of recovery accuracy and computational time under different data missing rates, is investigated on a few structural vibration response data sets—the seismic responses of the super high-rise Canton Tower and the structural health monitoring accelerations of a real large-scale cable-stayed bridge. Encouraging results are obtained and the applicability and limitation of the presented methods are discussed.

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1. Introduction

1.1. Motivation

Structural dynamics plays a critical role in many mechanical and civil engineering applications, such as modal based model updating [1], vibration based structural health monitoring (SHM) [2] and condition assessment [3]. Essentially, vibration measurement data is the basis for analysis of structural dynamic properties and performance. In civil engineering community, for example, many infrastructures are embedded with networks of sensors continuously measuring structural vibration responses, such as the California Strong Motion Instrumentation Program (CSMIP) [4], the SHM systems of the Canton Tower and the Stone-Cutter Bridge [5]. These measured vibration data is used for system identification and damage assessment as well as for the study of the dynamic characteristics of structures when subjected to ambient operational loads and extreme loads (such as earthquakes and hurricanes) in real-time and rapid post-hazard applications [6–10]. The effectiveness of these applications heavily relies on the accuracy and reliability of the vibration measurement data.

However, incomplete, randomly missing or corrupted data measurements of structural vibration responses often occur in structural dynamics. For example, structural vibration responses are often randomly corrupted by outliers (with unreasonably large magnitudes) due to sensor malfunction, instrumentation error, etc. Fig. 1 shows the ambient vibration responses of the Canton Tower recorded by the accelerometers of its SHM system [11]; it contains remarkable outliers (gross errors), which significantly corrupts the vibration measurements.

In wireless sensing platforms, data loss during wireless communication is a common issue. Researchers in the civil engineering community widely reported data loss, sometimes as high as 30%, when transferring structural vibration data using wireless platforms MICA, MICA2, and Imote2 [12–17]. Besides, to alleviate the wireless data sampling and communication burden, certain amounts of data are discarded during sampling or before transmission. For example, a new sampling paradigm, compressed sensing [18–20], has recently been studied in SHM and structural dynamics communities [21–27]; it states that it is possible to directly sample far fewer random measurements (than what is required by the sampling theorem), which are sufficient to capture all the information and recover a sparse signal. In addition, certain amounts of data can be intentionally discarded randomly before transmission in wireless sensor platforms due to limited power and communication resources (Fig. 2).

1.2. Problem statement & proposed approaches

In these and other applications, it is required to recover the original structural vibration responses from the available, incomplete data with many randomly missing (or corrupted) elements (Fig. 3). This is essentially an ill-posed inverse recovery problem, solving which requires additional information.

This study explicitly harnesses the unique data structure itself of the structural vibration responses to recover the missing data. This methodology relies on an empirical, but usually practically sound, observation—typically there are only few modes active in the structural vibration responses; hence, the single-channel structural vibration response vector has a sparse representation (in frequency domain), or, the multi-channel structural vibration response data matrix has a low-rank structure (by singular value decomposition). Such additional, prior, knowledge of data structure of structural vibration responses—intra-channel sparse or inter-channel low-rank—enables solving the ill-posed inverse problem of recovering the missing vibration response data.

Specifically, two convex optimization based methods for recovering missing or corrupted structural vibration response are established, using ℓ_1-minimization sparse vector recovery [28] and nuclear-norm-minimization low-rank matrix

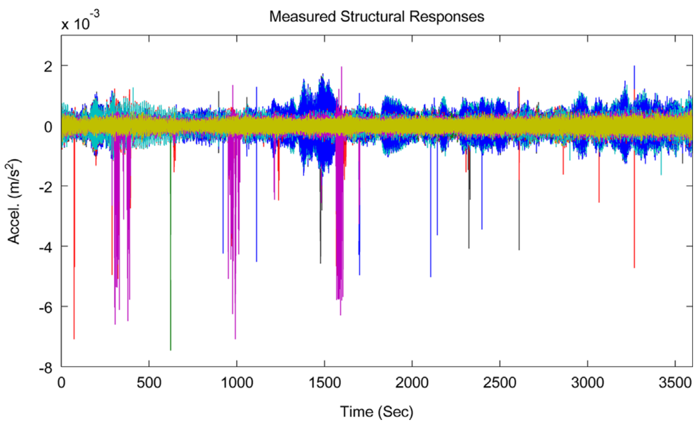

Fig. 1. The recorded ambient vibration accelerations of the Canton Tower from 12:00 am, Jan. 20th, 2010 to 1:00 pm, Jan. 20th, 2010. (20 channels data are shown, available in Ref. [11]).