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Vibration-based monitoring and diagnostics using compressive sensing ☆

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Vibration data from mechanical systems carry important information that is useful for characterization and diagnosis. Standard approaches rely on continually streaming data at a fixed sampling frequency. For applications involving continuous monitoring, such as Structural Health Monitoring (SHM), such approaches result in high volume data and rely on sensors being powered for prolonged durations. Furthermore, for spatial resolution, structures are instrumented with a large array of sensors. This paper shows that both volume of data and number of sensors can be reduced significantly by applying Compressive Sensing (CS) in vibration monitoring applications. The reduction is achieved by using random sampling and capitalizing on the sparsity of vibration signals in the frequency domain. Preliminary experimental results validating CS-based frequency recovery are also provided. By exploiting the sparsity of mode shapes, CS can also enable efficient spatial reconstruction using fewer spatially distributed sensors. CS can thereby reduce the cost and power requirement of sensing as well as streamline data storage and processing in monitoring applications. In well-instrumented structures, CS can enable continued monitoring in case of sensor or computational failures.

1. Introduction

Detecting and locating changes or faults in structures is an important field of research, as it has a direct impact on safety and reliability. During their service lifetime, structural components undergo and accumulate change in characteristics [1]. Early detection and location of these changes enable prolonged performance. In this regard, vibration-based monitoring is a well-established approach that is extensively documented in the literature [2]. Mechanical components such as shafts, wind turbine blades, etc. inevitably undergo vibrations in their operating environment. These vibrations inherently carry signatures in temporal and spatial domains that help indicate and locate changes in their characteristics [3,4]. Vibration-based detection methods are also popular in civil engineering structures such as bridges [5–7], for monitoring their structural health. A literature review of existing vibration-based monitoring and diagnostic techniques used in SHM is presented next.

Vibration-based SHM employs suitable in-situ active or passive transducers in order to analyze the characteristics of the structure in time, frequency, and modal domains [8–12]. Earliest approaches to this type of SHM involved comparison of

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modal properties of the damaged structure against an undamaged baseline of the same structure. Areas of application include structures such as bridges and wind turbines [4–6,13,14]. All vibration-based SHM methods rely heavily on time-history response of a structure that can be acquired using sensors such as accelerometers, strain gauges, etc. Modal parameters are then extracted by transforming the response into frequency domain [15].

Looking more closely, detecting changes in the natural frequencies of a structure remains important in vibration-based SHM [2]. It was shown that with increasing severity of damage, natural frequencies exhibited a more distributed shift as opposed to localized shift [10,16,17]. The effect of the geometry of damage on the shift was studied in [18,19]. Sensitivity of frequency shifts to damage and ambient variations has also been of interest [20,21]. In addition, experimental validations have been conducted on actual structures [22–24]. Frequency Response Functions (FRF) have been utilized to determine natural frequencies and their shifts [25–27]. Here, fault localization is suggested by collecting the FRF from multiple sensors at different locations of the structure [8,28,29]. *The review indeed confirms that while the shifting of natural frequencies is an indicator of structural change, it is not an effective means of locating the same*. This brings the topic of spatial characterization in SHM.

Mode shape extraction from the response of structures, for detection and localization of damage, is also popular [15,30]. One technique is direct comparison between a specific mode shape of a structure in its healthy and damaged states using either Modal Assurance Criterion (MAC) or Coordinate Modal Assurance Criterion (COMAC) [31,32,14]. A disadvantage of mode shapes based SHM is the large amount of data that is required in order to make reliable and accurate detection [8]. Additionally, mode shape data is polluted by noise and measurement errors that affect their sensitivity to damage. A solution to by-pass this problem can be to measure the first (slope) or second (curvature) derivatives of the mode shape itself [33]. Nevertheless, the mode shape based SHM method is widely studied and applied in experiments as well [8,34–44]. A related method of extracting spatial information is by reconstructing the Operational Deflection Shapes (ODS) [45]. ODS are superposition of mode shapes and provide a physical view of the vibration of a structure [8,46]. Other approaches, such as the use of transmissibility for detecting structural change [47], and use of correlation coefficients to distinguish strain data [48] have been explored in literature.

Other related techniques for structural monitoring include Guided Wave Testing (GWT) [49], imaging and pattern recognition [50], and Wavelet transforms [51–55]. Spatial wavelet analysis for damage detection and localization is a recent approach that has gained popularity. However, inherent distortions in wavelet transform induces the possibility that damages near the boundaries of structures may be undetectable. In [56], the authors address this drawback by employing a novel padding method to the vibration response while using Continuous Wavelet Transform. While a plethora of techniques are now available for SHM, they mostly involve instrumenting a given structure with as many sensors as possible. Thereafter, data extraction follows the traditional approach of Nyquist-Shannon's sampling theorem [57]. Advancements in sensor systems and the drop in their costs have led to sensing proliferation, but at the expense of data volume, computational burden and power-requirement [58].

As mechanical and civil engineering structures become more complicated and their performance standards are raised, monitoring and diagnostics will increasingly become more challenging. Hence, in spite of faster computational speeds and superior sensor technologies, it is imperative that the efficiency of condition monitoring be improved. Higher efficiency of monitoring implies reduced sensing requirement, low computational burden, and a greater flexibility of sensing. In [59], the authors recognized the importance of down-sampling and investigated its effect on damage detection in the spatial domain. In this paper, the application of Compressive Sensing (CS) to vibration-based monitoring [60], is proposed in order to achieve reduced sensing. While this approach is still in its nascent stages, an important related work in literature is [61], where the authors evaluated the ability of CS to compress vibration data from civil structures. In [62], spatial interpolation of the impulse response of a vibrating plate using sub-nyquist sampling was investigated. Spatial sparsity may also be exploited for source localization of acoustic waves [63,64]. For data reduction, the combination of vibration-based monitoring and CS is optimal, since the former offers sparsity which the latter fundamentally requires. The approach is also less reliant on mathematical modeling and model-based computations. This paper develops the foundation for CS based monitoring for lateral vibration of beams. Fundamentals of lateral beam vibrations and the effect of structural changes are discussed in Section 2. Sparsity of vibrations and the motivation for using CS are discussed in Section 3. Examples of CS and quantitative comparison with Nyquist-Shannon sampling approach are given in Section 4. The use of CS in detecting change in natural frequencies is established and demonstrated through simulations in Section 5. Thereafter, spatial reconstruction of deflection-shape through CS and its application in locating a fault is shown in Section 6. Preliminary experimental validation of CS for detecting shift in natural frequencies is presented in Section 7 using a cantilever beam setup. The quality of spatial reconstruction is analyzed in Section 8. Finally concluding remarks with a note on future scope of this research are made and references are provided.

2. Fundamental characteristics of beam vibrations

Fundamentals of beam vibration can be extended to analyzing vibration of practical mechanical structures. Hence, the study of beam vibrations is imperative and key to the development of the proposed research. The vibration characteristics of beams in their operating environment change with progression of faults or other introduced structural changes. In Sections 2.1 and 2.2, we discuss the basics of beam vibrations and demonstrate changes in vibration characteristics through

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