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Bayesian characterization of buildings using seismic interferometry on ambient vibrations

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ABSTRACT

Continuous monitoring of engineering structures provides a crucial alternative to assess its health condition as well as evaluate its safety throughout the whole service life. To link the field measurements to the characteristics of a building, one option is to characterize and update a model, against the measured data, so that it can best describe the behavior and performance of the structure. In this paper, we present a novel computational strategy for Bayesian probabilistic updating of building models with response functions extracted from ambient noise measurements using seismic interferometry. The intrinsic building impulse response functions (IRFs) can be extracted from ambient excitation by deconvolving the motion recorded at different floors with respect to the measured ambient ground motion. The IRF represents the representative building response to an input delta function at the ground floor. The measurements are firstly divided into multiple windows for deconvolution and the IRFs for each window are then averaged to represent the overall building IRFs. A hierarchical Bayesian framework with Laplace priors is proposed for updating the finite element model. A Markov chain Monte Carlo technique with adaptive random-walk steps is employed to sample the model parameters for uncertainty quantification. An illustrative example is studied to validate the effectiveness of the proposed algorithm for temporal monitoring and probabilistic model updating of buildings. The structure considered in this paper is a 21-storey concrete building instrumented with 36 accelerometers at the MIT campus. The methodology described here allows for continuous temporal health monitoring, robust model updating as well as post-earthquake damage detection of buildings.

1. Introduction

Vibration-based structural health monitoring (SHM) provides a primary tool for evaluating structural condition, integrity and reliability as well as for assessing potential risks throughout the lifecycle of structures. In recent years, topics on health monitoring of buildings have drawn great attention (to name a few, [1–10], among others). The vibrational measurements of the building can be responses induced by earthquake, ambient, or man-controlled excitations. Modal analysis of the vibrational records is commonly carried out to extract building characteristics such as damping ratios, resonant frequencies

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and mode shapes, using system identification techniques such as stochastic subspace identification [11], frequency domain decomposition [12], blind source separation [13], Bayesian operational modal analysis (OMA) [14–20], etc. It is worthwhile to mention that recent advances in Bayesian OMA showed that robust posterior probabilistic distributions of the modal parameters can be determined for given data and modeling assumptions without involving any stochastic averaging concept (see the work by Yuen et al. [14], Au et al. [15–18] and others [19,20] for example). The identified modal properties are then used for structural condition evaluation, model updating, and post-earthquake damage detection, etc.

Different from OMA widely used in building monitoring, Snieder and Şafak [21] proposed a deconvolution-based seismic interferometry approach to separate the impulse response functions (IRFs) of the building from the source of excitation and from the soil-structure interaction. The IRFs illustrate the propagation of shear waves (e.g., attenuation and scattering) inside the building, which are substantially composed of the building intrinsic characteristics such as the wave velocity, attenuation factor, resonant frequencies, mode shapes, etc. This approach has proven to be a successful and powerful technique for building monitoring under earthquake excitation, especially in one dimension (e.g., the translational direction) [22,3,23–25,9]. The IRFs as well as the associated characteristics are useful for building condition assessment. Nevertheless, the deconvolution interferometry mentioned above relies on natural source excitations such as earthquakes, which limits its applicability to continuous temporal health monitoring of buildings.

Recently, Prieto et al. [26] extended the deconvolution-based seismic interferometry approach to process a long duration of ambient noise measurements using a temporal averaging technique. The ambient vibration records were divided into overlapping windows and deconvolved with respect to a reference record window-by-window. Temporal averaging of the extracted waveforms for each window yields the overall IRFs of the building. This approach was successfully tested on the instrumented Factor building located at the campus of the University of California, Los Angeles. In another study, Nakata and Snieder [23] applied the deconvolution interferometry to the ambient vibration data of a building in Japan and obtained both causal and acausal waves propagating in the building for both positive and negative times. A string model was developed to quantitatively interpret the deconvolved IRFs. However, this model maybe too simple to describe the building's mechanical characteristics, and to be used for damage detection purposes. Similar to the OMA techniques (see [17] for example), the deconvolution interferometry method does not require knowledge of the input sources but assuming that they are statistically random when ambient noise data is used. Compared to the OMA methods, a distinctive feature of the interferometry approach is that the phase information can be well extracted for shear wave velocity estimation. Nevertheless, to remove the source effect using temporal averaging, the deconvolution interferometry approach requires a sufficiently long data set (see Section 2.1), which limits this approach to be applied to short period ambient measurements.

In this paper, we employ the extracted IRFs to update the finite element model of a building. The objective is to establish a baseline model, calibrated against field records, for building response prediction subjected to potential extreme events and for damage detection/quantification in future operations of the building. The majority of existing work in literature on model updating with output-only measurements such as ambient vibration records are based on structural modal parameters, e.g., frequencies, mode shapes, and frequency response functions (see [27–37] for example). In these approaches, the modal properties are commonly identified from the output-only measurements using OMA techniques mentioned previously and mode matching is performed in most cases. In general, the model updating strategies can be categorized into two groups, namely, deterministic vs. probabilistic. The deterministic approaches (e.g., constrained optimization [38,31,32], sensitivity method [39–41], heuristic optimization [28,42]) aim to tune parameters so that the updated model can best predict the measured data, while the probabilistic methods use Bayesian inference and make possible to identify a set of plausible models with probabilistic distributions and to characterize the modeling uncertainties [29,30,43,34,44–46,35–37,47]. For example, Au and Zhang [48,49] proposed a two-stage formulation successfully applied to Bayesian modal identification and updating of structural model parameters using ambient vibration data.

Instead of using the modal quantities, we herein apply the hierarchical Bayesian inference to update the finite element model of a building against the IRFs extracted from ambient vibration records using deconvolution interferometry. The model parameters are quantified using a Markov chain Monte Carlo (MCMC) technique with adaptive random-walk steps for sampling. Straightforward response (IRFs) matching at observation locations is recursively performed in the Bayesian updating process for given modeling assumptions.

This paper is organized as follows. Section 2 presents the deconvolution interferometry approach for building response extraction using ambient vibration records. Section 3 describes the probabilistic model updating framework based on hierarchical Bayesian inference and the MCMC sampling technique with adaptive random-walk steps for parameter uncertainty quantification. In Section 4, a 21-storey concrete building instrumented with 36 accelerometers at the MIT campus is studied to validate the performance of the proposed approach for continuous monitoring and model updating of buildings. Finally, Section 5 gives the discussions and conclusions.

2. Extracting building response using seismic interferometry

The vibration of a building is related to the excitation, the soil-structure interaction, and the building mechanical properties [21]. Separating the building response from the excitation and the soil-structure interaction using vibrational data yields information of the intrinsic characteristics of the building. We herein apply a seismic interferometric method to extract the shear waves propagating in the building, identical to the IRFs, based on deconvolution [21,22,3,26,50,23,24]. The