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Phase space interrogation of the empirical response modes for seismically excited structures

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A R T I C L E I N F O

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Conventional Phase Space Interrogation (PSI) for structural damage assessment relies on exciting the structure with low dimensional chaotic waveform, thereby, significantly limiting their applicability to large structures. The PSI technique is presently extended for structure subjected to seismic excitations. The high dimensionality of the phase space for seismic response(s) are overcome by the Empirical Mode Decomposition (EMD), decomposing the responses to a number of intrinsic low dimensional oscillatory modes, referred as Intrinsic Mode Functions (IMFs). Along with their low dimensionality, a few IMFs, retain sufficient information of the system dynamics to reflect the damage induced changes. The mutually conflicting nature of low-dimensionality and the sufficiency of dynamic information are taken care by the optimal choice of the IMF(s), which is shown to be the third/fourth IMFs. The optimal IMF(s) are employed for the reconstruction of the Phase space attractor following Taken's embedding theorem. The widely referred Changes in Phase Space Topology (CPST) feature is then employed on these Phase portrait(s) to derive the damage sensitive feature, referred as the CPST of the IMFs (CPST-IMF). The legitimacy of the CPST-IMF is established as a damage sensitive feature by assessing its variation with a number of damage scenarios benchmarked in the IASC-ASCE building. The damage localization capability, remarkable tolerance to noise contamination and the robustness under different seismic excitations of the feature are demonstrated.

1. Introduction

Interrogation of structures are essential to acquire information about the "health" of a structure, in view of incipient damages that may occur during their service lifetime. This process is referred as Structural Health Monitoring (SHM). The SHM assess the state of structures (stiffness and/or strength) due to changes in the material properties, geometric dimensions or boundary conditions. Earlier technologies for the SHM are visual inspection and nondestructive testing [1]. However, these techniques require full access to the structure that might not be feasible. Manual inspections are also time and resource consuming. Further, all type of damages cannot be detected by eyes. In fact, hidden damage(s) in structures resulted in a number of failures in the past that have triggered the development of the modern SHM methodologies. Modern SHM is automatic, continuous, robust and reliable in real time performance. The SHM not only provides information about the structural health under aging and degradation from operational environment but also helps in rapid assessment and screening after an extreme event (e.g. earthquake) for the safe occupancy and reuse of a structure.

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Modern SHM involves sensor network for continuous monitoring of structural responses, which are subsequently processed for extracting information on structural health [2,3]. Statistical analysis are also taken up to assess the robustness of the feature with respect to severity and localization of damage. The SHM works at several level, Level-I refers to detection of damage in the structure, level II identifies the location of the damage, Level-III would identify the type of damage and the quantification of damage is done in Level-IV. Finally, Level (V) predicts on the remaining lifetime and prognosis [3].

Although, the SHM involves several components, the principal challenge to the structural engineers is the analysis of the sensed response(s) in order to extract effective information on structural damage. The SHM methodologies can be broadly classified into two categories, one is the System Identification (SI) based methods, and the other is based on extraction of damage features indicating the presence of damage(s). The SI methodology directly estimates the structural parameters from the responses measured at several locations of the structure by using an optimization algorithm. Although most of the SI methodologies deal with the linear systems, identification of nonlinear systems have also been tried with limited success [4–8]. However, the system identification approach becomes prohibitively exhaustive for large structures with significant amount of nonlinearities and the problems may suffer from non-uniqueness [9,10].

The feature based techniques extract damage sensitive features from the responses collected at several locations of the structure and relate them to the extent and location of damage(s). Most common damage sensitive features are the change in natural frequencies [11], change in mode shape curvature [12], Auto Regressive and Moving Average (ARMA) coefficients in the predictive time series model [13], Wavelet based techniques [14] and so on. A review of these vibration based methodology can be obtained from Doebling et al. [15] and Sohn et al. [16].

Recently, several damage features based on the phase space representation of the system dynamics are proposed. At motion, the dynamical states of a structure trace out certain geometry in phase space, referred as Phase portrait. It has been demonstrated that the damage(s) in the structures can be correlated with certain properties of the phase portrait [17]. The superiority of these features are established over the conventional modal features [18]. The phase portrait based techniques are also readily extendible to nonlinear structures due to incipient damage. The aspect of nonlinearity are often overruled in the conventional SHM methodologies, partly because of their inability to accommodate nonlinearity. Commonly reported damage features based on the disparities of the phase portrait(s) are, the Local Attractor Variance Ratio (LAVR) proposed by Todd et al. [19], Phase Space Warping (PSW) suggested by Chelidze and Liu [20], change of Phase Space Topology (CPST) by Nie et al. [21,22]. A basic requirement of these techniques is that the structure must be excited by a low dimensional chaotic signal to ensure that the low dimensionality of the phase portrait is maintained. Similar methodology under stochastic excitations have also been reported [23,24]. Improvement in the chaotic interrogation based feature are made by employing the hyper-chaotic excitation by Torkamani et al. [25]. Although phase portrait based damage detection methodologies based on linear/nonlinear dynamic responses received considerable attention, its applicability to large scale structural system is limited by the fact that, exciting a structure by chaotic waveform poses practical difficulty. The suitability of the PSI can be enhanced largely, if instead of chaotic waveform, the natural excitations can be made use of.

With this being the eventual goal, in this study, an attempt is made to use the measured responses of the structures, subjected to seismic excitations, for use in the PSI. In this regard, it may be pointed out that similar attempt have been made by Nichols [26] using the hydrodynamic wave excitations for the SHM of offshore structure. However, the wave excitations and the structural responses are low dimensional. The present work extends the chaotic interrogation procedure for the SHM of structures subjected to earthquake excitations, which are known to be high dimensional and difficult to embed in phase space using the Taken's theorem. The IASC-ASCE benchmark building is selected as the structure to obtain its response(s) under recorded ground accelerations. These responses are taken as the measured responses to assess the incipient damage(s), localization and severity. Five damage scenarios, benchmarked in the IASC-ASCE building are adopted for numerical elucidation. The difficulty associated with the high dimensionality of the seismic responses are overcome with the help of EMD, decomposing a high dimensional signal with a few relatively low dimensional components, referred as Intrinsic mode Functions (IMFs). The IMFs retain significant portion of the dynamics to reflect their sensitivity towards the induced damage scenarios. The CPST features pertaining to individual IMFs (referred as IMF-CPST) are then assessed for their suitability as the damage features. The robustness of this feature is assessed under varying degree of noise contamination as well as alternative set of seismic excitations.

2. Phase portrait and extraction of the damage feature

The PSI involves several steps. The measured responses are first decomposed into a number of low dimensional IMFs through EMD, so that the IMFs are amenable to low dimensional embedding, following the Taken's embedding theorem [27,28]. The Singular System Analysis (SSA) is performed on the so-obtained IMF(s) in order to assess their dimensionality for embedding. The lag coordinate for their phase space reconstruction is estimated from the Average Mutual Information Function (AMIF) of the respective IMF(s). The reconstructed phase portraits from the damaged and undamaged structures are analyzed for the CPST and correlated with the different damage scenarios in the structure. Details of these are expanded in the subsequent sections.