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Detection of multiple damages employing best achievable eigenvectors under Bayesian inference

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ABSTRACT

A novel approach is presented in this work to localize simultaneously multiple damaged elements in a structure along with the estimation of damage severity for each of the damaged elements. For detection of damaged elements, a best achievable eigenvector based formulation has been derived. To deal with noisy data, Bayesian inference is employed in the formulation wherein the likelihood of the Bayesian algorithm is formed on the basis of errors between the best achievable eigenvectors and the measured modes. In this approach, the most probable damage locations are evaluated under Bayesian inference by generating combinations of various possible damaged elements. Once damage locations are identified, damage severities are estimated using a Bayesian inference Markov chain Monte Carlo simulation. The efficiency of the proposed approach has been demonstrated by carrying out a numerical study involving a 12-story shear building. It has been found from this study that damage scenarios involving as low as 10% loss of stiffness in multiple elements are accurately determined (localized and severities quantified) even when 2% noise contaminated modal data are utilized. Further, this study introduces a term *parameter impact* (evaluated based on sensitivity of modal parameters towards structural parameters) to decide the suitability of selecting a particular mode, if some idea about the damaged elements are available. It has been demonstrated here that the accuracy and efficiency of the Bayesian quantification algorithm increases if damage localization is carried out a-priori. An experimental study involving a laboratory scale shear building and different stiffness modification scenarios shows that the proposed approach is efficient enough to localize the stories with stiffness modification.

1. Introduction

Any kind of structural damage in a building, bridges etc. causes change in the associated structural parameters (e.g., stiffness) and results in changes in the dynamic properties of the system such as natural frequencies and mode shapes. Utilizing this concept, damage in a structure is often identified by evaluating the dynamic properties of the structure through measured responses. For the past several years, extensive research has been carried out with an emphasis on identifying damage or knowing the current condition of civil, mechanical, or space structures. With the advancement in sensors and data acquisition technologies, various damage detection algorithms have been proposed so far for civil engineering structures. Many of these algorithms directly employ the measured modal data (e.g., frequency and mode shape) for damage detection or system

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identification purpose [1–8].

Fan and Qiao [9] provides a good review of modal parameter-based damage identification methods for beam- or plate-type structures. Since mode shapes contain local information and are less likely to get affected due to varying environmental conditions, the techniques based on mode shapes have widely been used for damage localization [9–11]. Theoretical basis for change of mode shape due to change in stiffness can be found in Roy and Ray-Chaudhuri [7], Ray-Chaudhuri [12], Ghosh and Ray-Chaudhuri [13].

Although most of these algorithms can successfully determine the damage in a structure wherein a single structural element is damaged, performance of these algorithms is not so appealing in case of simultaneous damage in many elements, particularly while dealing with noisy data. A good review of these developments can be found in Doebling et al. [14], Doebling et al. [15], Alvandi and Cremona [16] and Yan et al. [17]. In a recent study, Roy et al. [18] have proposed several auto-regressive model-based damage sensitive features for structural damage localization using output-only measurements and shown that the performance of these features varies depending upon the noise and structural damping levels.

A few studies of damage detection techniques use the concept of best achievable vector of a space or subspace, where the damaged elements of a structure are determined by evaluating the Euclidean distances between the measured parameter vector (e.g. flexibility parameter vector or mode shape vector) and the best achievable vector of a subspace. The considered subspace is formed such that it specifically relates to the damaged elements of the structure. Lim and Kashangaki [19] proposed an algorithm using the concept of best achievable eigenvector to determine the damage in a space truss structure. In this approach, at first, the location of damaged element is determined using best achievable eigenvector concept and then the magnitude of damage is determined by solving the associated equations for the reduction factor. For multiple damage case, a sequential approach was adopted. This includes (i) the detection of most probable damaged element by examining the Euclidean distances between the measured and the best achievable eigenvector for each considered mode, (ii) determining the magnitude of damage for the identified element, (iii) modifying the undamaged mass/stiffness matrices for the identified magnitude of damaged element, and (iv) repeating the process till all damaged elements and their magnitudes are identified. It may be observed from these steps that the theoretical construct of the aforementioned approach is restricted to damage in single element and thus, the approach requires iterative process for multiple damage locations as reported by Bernal [20]. Zhao and Zhou [21] used the concept of best achievable eigenvector to determine damage in shallow arches. The concept of best achievable eigenvector is further extended to best achievable modal eigenvector by Ricci [22] for structural damage detection. In a recent study by Prajapat and Ray-Chaudhuri [23], the issue of damage detection with highly noise contaminated data has been dealt with the best achievable eigenvector technique under Bayesian framework. However, the theoretical construct of the technique presented in this work is also limited to single element damage detection only and does not address the procedure of damage localization in a structure. The best achievable eigenvector concept is also utilized in a few eigenstructure assignment-based structural damage detection approaches [24,25]. Some studies [26,27] employed the concept of best achievable vector in terms of structural flexibility change to determine the structural damage.

In presence of factors such as noise in data and difficulties in achieving a true mathematical model and insufficient measurements, a deterministic approach for damage detection in structures may suffer with non-unique solution. In past few decades, the issue of non-uniqueness of solution of deterministic problems is taken care by resolving the problem in a statistical framework under Bayesian inference. In recent years, many Bayesian algorithms have been proposed for damage detection or system identification purpose [28–40]. The unknown parameters of the structure are identified employing either modal data or the direct time history responses of the structure [38,41–44]. Incomplete and noisy modal data are employed by Sohn and Law [45] under Bayesian probabilistic approach to detect damage in structures. An online Bayesian health monitoring approach was proposed by Vanik et al. [41]. To detect damage in a structure, at first the structure is identified in its undamaged state and then, the damage assessment is carried out by running continues health monitoring cycles. Some studies also focused on selection of appropriate model class in Bayesian framework for structural identification and damage assessment purpose [36,46]. Different types of structures are considered under Bayesian framework for damage detection purpose by many researchers, e.g., a steel cantilever beam [47], plate type structures [48], and 7-story RC building [49].

All the aforementioned studies deal with damage detection in a structures as a system identification problem. A system identification problem treats all the major structural parameters as unknown and evaluates these using measured data of the structure. In large structures, treatment of all parameters as unknown enforces the identification problem to deal with a very high dimensional space. This makes the Bayesian algorithm computationally inefficient. However, if the intact structure can be determined within permissible error limits using the as-built structural design/drawings or other available information, the dimensionality of the Bayesian problem can be reduced. This can be achieved by first localizing the damaged elements and then treating only these elements as unknown in the algorithm.

This study proposes a novel approach for localization and quantification of damage in multiple elements of a structure simultaneously. For this purpose, a best achievable eigenvector concept based formulation has been derived to detect damage in multiple elements. The formulation is embedded in Bayesian inference to address the problem in a meaningful way, particularly while dealing with noisy data. It may be noted that the Bayesian framework allows to evaluate the relative plausibility of each damage combination. Moreover, unlike the existing best achievable eigenvector approach, the proposed approach under Bayesian framework can combine data from more than one mode directly for a better damage detection. The approach works as follows: at first, the number of damaged elements are evaluated, then damage locations are identified and finally, the severities of damage are estimated. Further, this study demonstrates the suitability of selecting a particular mode for damage identification. A term *parameter impact* is introduced for this purpose to evaluate the influence of a parameter on a particular mode.