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Structural damage detection using sparse sensors installation by optimization procedure based on the modal flexibility matrix

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ABSTRACT

This paper is aimed at presenting a novel and effective method to detect and estimate structural damage by introducing an efficient objective function which is based on Modal Assurance Criterion (MAC) and modal flexibility matrix. The main strategy in the proposed objective function relies on searching a geometrical correlation between two vectors. Democratic Particle Swarm Optimization (DPSO) algorithm, a modified version of original PSO approach, is used to minimize the objective function resulting in the assessment of damage in different structure types. Finally, the presented method is generalized for a condition in which a limited number of sensors are installed on the structure using Neumann Series Expansion-based Model Reduction (NSEMR) approach. To evaluate the efficiency of the proposed method, different damage patterns in three numerical examples of engineering structures are simulated and the proposed method is employed for damage identification. Moreover, the stability of the method is investigated by considering the effects of a number of important challenges such as effects of different locations for sensor installation, prevalent modeling errors and presence of random noises in the input data. It is followed by different comparative studies to evaluate not only the robustness of the proposed method, but also the necessity of using introduced techniques for problem solution. Finally, the applicability of the presented method in real conditions is also verified by an experimental study of a five-story shear frame on a shaking table utilizing only three sensors. All of the obtained results demonstrate that the proposed method precisely identifies damages by using only the first several modes' data, even when incomplete noisy modal data are considered as input data.

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1. Introduction

In the field of structural maintenance, Structural Health Monitoring (SHM) has received considerable attention in the recent years. As the main part of SHM programs, damage localization and quantification strategies can provide basic information about the health of structural systems. Generally, researchers try to find reasonable, simple and practical approaches for damage identification by analyzing structural feedback and/or response. Most of these methods are based on inspecting vibrational characteristics of monitored structures. Vibrational data, such as modal data, depend directly on the physical properties of structure, therefore, damage or changes in the physical characteristics, such as change in structural stiffness, can be identified by inspecting vibrational data [1]. A complete review of these approaches can be found in [1,2].

From the formulation viewpoint, vibration-based methods can be divided into two major groups. First group are approaches in which a direct methodology is introduced for damage identification. Such an aim was achieved by performing signal processing-based procedures [3–6], soft computation approaches [7,8], and mathematical analysis [9–16].

The second group of vibration-based methods are defining damage detection problem as an inverse problem and solving it by employing optimization procedures [17–24]. Teughels and De Roeck [18] suggested a finite element model updating approach for damage identification and combined two traditional optimization algorithms for solving the presented problem. Perera et al. [25] introduced single and multi-objective functions for damage prognosis by considering changes in both natural frequencies and mode shape vectors, and found optimal solution by means of Genetic Algorithm. Ghodrati Amiri et al. [26] employed free vibration equation for addressing damage detection problem and utilized Pattern Search and Genetic optimization algorithms for finding optimal solution. They demonstrated the applicability of their method by studying different damage patterns on plates. Na et al. [21] evaluated flexibility changes via Genetic Algorithm for damage identification in shear buildings and studied the impacts of mass errors on the robustness of their method. An optimization-based approach by considering natural frequency changes was proposed by Saada et al. [27] for defect identification in beams. They used Particle Swarm Optimization (PSO) and identified different kind of simulated damages in numerical and experimental studies. Nanda et al. [24] applied Unified Particle Swarm Optimization (UPSO) for crack identification in frame like structures. Recently, Zare Hosseinzadeh et al. [28] suggested a method for detecting structural damage by employing Cuckoo Optimization Algorithm (COA). They verified their method by studying different numerical and experimental examples. Although these methods can effectively detect structural damage, they use all members of the calculated features from modal data or use a large number of modal data for constructing damage-sensitive cost functions. Furthermore, most of them follow a direct data-fitting strategy for proposing cost functions. Since using many recorded data by a direct data-fitting approach may intensify the noise effects, in the present paper a novel cost function is suggested that not only uses just some entries of the calculated damage-sensitive features, but also employs a geometrical tracing-based strategy for cost function formulation.

The other practical challenge in the mentioned damage detection methods is related to equipping all degrees of freedom (DOFs) with sensors. Generally, because of some difficulties in recording data, especially from rotational DOFs, accessing to approaches which can detect structural defects by installing sparse sensors is preferable. There is a little number of methods which have been devoted to solving this challenge. Some researchers employed the expansion of mode shapes' data [29–31] and others used matrix condensing approaches [32–34], for providing a condition in which a limited number of sensors are utilized for damage identification. This paper proposes a method which tries to solve this challenge by employing a simple, novel and practical strategy for condensing analytical structural model (i.e. mass and stiffness matrices) compatible with real behavior of the structure. In addition, it is aimed to develop a procedure requiring as few modal data as possible. Generally, using more data may lead to more accurate results; however, as it is mentioned, intensification of noise effects and existing of probable erroneous in acquired data may make it undesirable to employ. Therefore, those methods utilizing as few as possible input data for damage identification are more reasonable and practical, especially in SHM of complex structures.

By considering above mentioned challenges, this paper attempts to present a novel method which

- considerably decreases the effects of noise and modeling errors, and also increase the sensitivity of the method by introducing a new damage-sensitive, geometrical-based cost function;
- uses only the first several incomplete modal data as input data;
- employs one-stage model reduction approach to simulate an accurate model of real behavior of the monitored structure which is equipped with a limited number of sensors;
- uses a robust optimization algorithm for solving ill-posed inverse problems with a high level of accuracy without trapping by local extremums.

In the proposed method, at first, the flexibility matrix of the monitored structure is calculated by means of only the first several modes' data. In order to make the procedure fast in converging to results, only some entries of the calculated flexibility matrix are selected and stored in vector format. Then, such a vector is computed for analytical model of the structure (with unknown damage) and a new cost function is introduced by employing a geometrical criterion for measuring the amount of correlation between two vectors. Although due to the some practical limitations proposing such a methodology is required, it may lead to more complexity in the problem. Therefore, to solve this cost function, a robust optimization algorithm should be utilized that not only can use the ability of all candidate solutions for finding global

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