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Research paper

An efficient approach for optimal sensor placement and damage identification in laminated composite structures

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ABSTRACT

This paper proposed an efficient approach for optimal sensor placement and damage identification in laminated composite structures. This approach first utilized a model reduction technique, namely iterated improved reduced system (IIRS) method, to develop a reduced order model for optimal sensor placement (OSP), and then the OSP strategy using Jaya algorithm is conducted by formulating and solving an optimization problem for finding the best sensor locations. The objective function of the optimization problem is defined based on the correlation between the flexibility matrix obtained from an original finite element model and the corresponding one calculated from IIRS method. Next, the approach uses the measured incomplete modal data from optimized sensor locations for detecting and assessing any stiffness reduction induced by damage. In order to do this, the damage identification problem is formulated as an optimization problem where the damage extent of elements and the modal flexibility change are taken as the continuous design variables and the objective function, respectively. The Jaya algorithm is again adopted to solve the optimization problem for determining the actual damage sites and extents. Numerical simulations of a three cross-ply (0°/90°/0°) beam and a four-layer (0°/90°/90°/0°) laminated composite plate are carried out to demonstrate the applicability and efficiency of the proposed approach.

1. Introduction

With significantly increasing applications of composite materials in mechanics, aerospace, marine, civil and many other industries, structural health monitoring (SHM) for composite materials have gained much attention from the scientific and engineering communities. A reliable and effective damage diagnose method is extremely important to ensure the conditions of integrity and safety of structures made of composite materials. Over the last few decades, many works and studies have been focused on vibration-based global SHM techniques for solving damage identification problems in composite structures. The basic idea of these techniques is that the change of either modal parameters (natural frequencies [1], mode shapes [2]) or their variations (frequency-response function [3], curvature mode shapes [4], flexibility matrix [5], etc.) can be used as signals to detect and locate damages in the structures. For more detailed information on these techniques, the reader can refer to good review articles [6,7]. Besides, several recent studies related to flaw detection problems in smart composite structures were presented in Refs. [8–10].

In essence, the problem of damage identification in composite structures can be formulated as an optimization problem, where the location and degree of damage are found by minimizing the objective function which is commonly defined in terms of the difference between the vibration data measured by modal testing and those calculated from analytical model. For generating data from the analytical model used in health monitoring studies, the damage can be simulated by either reducing the stiffness of elements in damaged areas [5,11,12] or using crack models [13–15] or delamination models [16–18]. As a result, the traditional finite element (FE) analysis or isogeometric analysis [19–22] can be employed as a tool for damage diagnosis through the model updating process which typically requires an optimization algorithm. In order to meet this requirement, several meta-heuristic optimization algorithms have been applied as intelligent searching techniques to deal with the problem. For example, Su et al. [16] used genetic algorithms (GAs) and artificial neural networks (ANNs) for quantitative assessment of delamination in glass fiber-reinforced epoxy (GF/EP) composite laminates. In their study, the efficiency of the GA was compared with ANNs in term of both the prediction precision and computational cost. Qian et al. [17] proposed a hybrid optimization algorithm featuring cooperative particle swarm optimization (PSO) with simplex method

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(SM) for identification of delamination in laminated composite beams. Vosoughi and Gerist [11] presented a hybrid method based on continuous genetic algorithm (CGA) and PSO for damage detection of laminated composite beams. In their work, nevertheless, the effect of measurement noise on the accuracy of the hybrid method was not investigated. More recently, a few studies have been focused on plate-like structures. Ashory et al. [23] used GA to solve the optimization problem for damage location and intensity identification in composite plates. Dinh-Cong et al. [12] introduced an efficient multi-stage optimization procedure using a modified differential evolution algorithm (MS-MDE) for damage assessment in a laminated composite plate.

It is noted that the above-mentioned researches required full FE models to be able to determine accurately and completely the vibration characteristics in composite structures, which restricts applicability to real-world and large-scale implementations. Given that in practical situations it is almost impossible to determine entire experimental modal information corresponding to every node/ degree of freedom (DOF) of the FE structural model because the number of measurement sensors is typically limited, especially for large-scale structures. Therefore, one of the practical challenges to the problems of damage identification in composite structures is the use of incomplete modal data instead of complete modal data in calculation due to the limited number of measurement sensors used in practice. However, there have not been many reported studies in the literature for dealing with this challenge [1,18].

Generally, the more sensors are placed on a structure, the more information from measurement data can be obtained. However, due to cost and practicality issues, there are usually only a small number of sensors installed to a predefined set of possible locations. In fact, the quality of these data, as well as the quality of damage prediction depends much on the placement of sensors, and hence optimal sensor placement (OSP) is an important constituent in the SHM of composite structures. In the last two decades, many techniques have been proposed and developed to achieve OSP which can help collect the best identification of structural characteristics. An overview of OSP techniques was presented by Yi and Li [24]. Among them, combinatorial optimization methods have been widely employed owing to its computational efficiency for solving OSP problems of large-scale structures. Recently, some meta-heuristic optimization algorithms such as improved particle swarm optimization (IPSO) algorithm [25], niching monkey algorithm (NMA) [26], firefly algorithm (FA) [27], artificial bee colony (ABC) algorithm [28] have been successfully applied to the OSP problems. Nevertheless, there are still several issues for further improvement such as: (1) how to reduce significantly the computational cost of the optimization algorithms; (2) how to validate the optimal sensor layout obtained from the OSP strategies via a damage detection technique; and (3) how to minimize the number of sensors used for the problem of structural damage diagnosis.

As an effort to fill in the above-mentioned research gaps, the current paper hence proposes an efficient approach for optimal sensor placement and damage identification in laminated composite structures. The main contributions of the paper can be addressed in three following aspects: (i) Propose a more effective OSP strategy for finding proper sensor locations installed on laminated composite structures; (ii) Conduct an optimization-based damage detection technique to validate the optimal sensor layout obtained from the proposed OSP strategy for structural damage detection, simultaneously showing its capacity in damage diagnosis and assessment by using the first several lower incomplete modes; and (iii) Apply effectively the Jaya optimization algorithm for solving both OSP and damage diagnose problems without trapping into local optima. The present work has two main parts. The first one is to determine the optimal location of a given limited number of sensors placed on a structure. For this purpose, we use a model reduction technique, namely iterated improved reduced system (IIRS) method [29], to develop a reduced order model for OSP, and then Jaya algorithm as robust optimization tool [30–32] is adopted to determine the optimal location for a given set of sensors. The correlation between the flexibility matrix obtained from an original FE model and the corresponding one calculated from IIRS method is considered as the objective function, where the sensor positions are defined to be the discrete optimization variables. We also present a comparison between the proposed objective function with an objective function based root mean square (RMS) of modal assurance criterion (MAC) [33,34] to validate the superiority of the proposed objective function. The second one is to locate and quantify structural damage using incomplete modal data obtained from optimized sensor locations. In this second part, the optimization-based damage identification problem is first formulated by defining the damage extent of elements as the continuous design variables and the modal flexibility change as the objective function, and then solved by using again the Jaya algorithm. To investigate the applicability and efficiency of the proposed damage diagnosis approach, two numerical examples including a three cross-ply (0°/90°/0°) beam and a four-layer (0°/90°/90°/0°) laminated composite plate are conducted. In addition, the influence of noise in the measured incomplete modal data on the accuracy of proposed approach is also examined in the examples.

The remaining parts of the article are organized as follows. Initially, the IIRS method for OSP is presented in Section 2. Then, Section 3 generally provides the formulation of optimization-based damage detection problem. In Section 4, the description of the Jaya algorithm for discrete and continuous design variables is introduced. Section 5 shows the performance of the proposed approach through numerical examples. Finally, the concluding remarks are given in Section 6.

2. Formulation of optimal sensor placement problem

In this section, the mathematical formulation of optimal sensor placement (OSP) strategy is conducted by considering three following main points: (1) the OSP as an optimization problem; (2) the iterated improved reduced system (IIRS) method; and (3) the objective function for OSP problem. The details of the three points are presented in the next three sub-sections.

2.1. Optimal sensor placement as optimization problem

The main goal of OSP in SHM is to determine the optimal sensor layout that can collect as much information of structural dynamic characteristics as possible. To achieve this goal, the OSP problem can be formulated as a constrained optimization problem in which the sensor positions are considered as the discrete design variables and the constraint is typically a given limited number of sensors. The objective function, usually based on the dynamic characteristics of a structure, can be maximized or minimized to determine the optimal locations for a given limited set of sensors. Thus, the mathematical model of OSP problem can be defined by the following optimization equation.

$$\begin{aligned} &\min f(\mathbf{S}),\ s \in \mathbb{Z}^+ \\ &s.\ t.\ g(\mathbf{S}) = n, \\ &\mathbf{S}^{lb} \le \mathbf{S} \le \mathbf{S}^{ub}. \end{aligned} \tag{1}$$

where f is the objective function;$\mathbf{S} = (s_1,s_1, \dots, s_n)$ is denoted as the candidate sensor locations placed at nodes/ DOFs of the FE structural model; n is the given limited number of sensors; $\mathbf{S}^{lb}$ and $\mathbf{S}^{ub}$ represent the vectors of lower and upper bound of $\mathbf{S}$, respectively; and $\mathbb{Z}^+$ is the set of positive integers.

In the OSP problem, a numerical model is required to identify the modal parameters of structural system such as natural frequency and mode shapes. Nevertheless, such a model will have many more nodes/ DOFs, while the optimal potential sensor locations are only chosen from a subset of the total nodes/ DOFs. Hence, we use a model reduction technique, namely IIRS method [29], to eliminate those DOFs that do not relate to the candidate sensor locations required. A brief description