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A two-step approach for damage detection in laminated composite structures using modal strain energy method and an improved differential evolution algorithm

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ABSTRACT

The paper presents a two-step approach based on modal strain energy method and an improved differential evolution algorithm for damage detection in laminated composite structures. First, the modal strain energy based method is employed to identify a set of potential damaged elements. Then, the improved differential evolution algorithm is utilized to minimize the function of mode shape error with design variables relating to the extent of identified damaged elements. Here, the function of mode shape error is defined by the shift between the mode shape of the damaged structure and that of the healthy structure. The proposed approach is applied for a cross-ply (0°/90°/0°) laminated composite beam and a cross-ply (0°/90°/0°) square laminated composite plate with multiple damaged elements. In addition, the effect of noise on the accuracy of damage identification is also investigated. Numerical results show that the proposed approach is effective for damage detection in laminated composite beam and plate structures for both cases with noise and without noise.

1. Introduction

Due to outstanding properties, such as light weight, high stiffness and strength, etc., the composite materials have been used widely and popularly in many different engineering disciplines such as civil infrastructures, aerospace and automotive engineering. Damage in composite structures may significantly reduce their stiffness and then lead to tragic consequences. As a result, the development of reliable and efficient damage identification methods for composite structures is really necessary.

In the structural health monitoring (SHM) literature, vibration-based damage detection methods are widely used for composite structures. Reviews of these methods can be found in Refs. [1–4] and their application for composite structures is reported in [5,6]. In the categories of vibration-based damage detection methods, frequency change-based method [7,8], curvature mode shape-based method [9,10], modal strain energy based method [11,12], flexibility based approach [13] and mode shape based method [14] have been applied successfully for composite structures like beams and plates. Besides, some other damage identification methods, such as wavelet analysis method, optimization-based method, guided Lamb wave method [15] also employed to identify the damage location on composite structures. Although there were amount of damage assessment methods based on vibration characteristics for composite structures, most of them were limited to damage location only.

There have been some damage identification methods based on the optimization algorithms which were used to identify the location and extent of damage [4,16–19]. The main idea of these methods is to transform the damage identification problem into an optimization problem in which the objective function is usually defined by minimizing the difference between measured and analytical model characteristics of the structure and the design variables are the damage ratios of elements in the structure. Several meta-heuristic optimization algorithms such as genetic algorithm (GA), particle swarm optimization (PSO), artificial bee colony (ABC) have been applied successfully for structural damage localization [16,20,21]. One important advantage of this approach is that the complete set of model characteristics (e.g. modes or displacements) is not needed because the objective function involves only the difference of main components of these vectors [22].

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Another advantage of this approach is that they can determine both location and extent of structural damage. However, the application of this approach for composite structures is still somewhat limited. Besides, the implementation of optimization algorithms for locating damage in structures still has some drawbacks that need to be addressed. For example, (1) the accuracy of the optimization algorithms, (2) the expensive computational cost of the optimization algorithms, (3) the invalid of the optimization algorithms for dealing with large design variables.

Among population based meta-heuristic algorithms (e.g. particle swarm optimization (PSO), artificial bee colony (ABC), and cuckoo search (CS), etc.), the differential evolution (DE) algorithm, firstly introduced by Storn and Price [23], has been proven to be one of the most promising methods when it was evaluated for over fifty different benchmark functions [24]. It also has been successfully applied and developed for numerous problems in various fields such as communication [25], mechanical engineering [26–29], structural health monitoring [30,31], artificial neural network training [32], and so forth. Nevertheless, similar to many other meta-heuristic algorithms, the main limit of the DE also concerns with the high computational cost [33–35].

This paper hence makes an effort to fill in the above mentioned research gaps by proposing a two-step approach for damage identification in laminated composite structures by means of using a modal strain energy based method and a newly improved differential evolution algorithm. Firstly, the modal strain energy based method referred to [36] is used to identify possible damage elements, and also to reduce the design variables of the optimization problem for the second step. Secondly, an improved differential evolution algorithm is utilized to assess the extent of damage and also to reduce the false alarms of elements found in the first step. The improvements on the DE are made in mutation and selection phases to reduce the computational cost of the algorithm. The numerical examples consider a cross-ply (0°/90°/0°) laminated composite beam and a cross-ply (0°/90°/0°) square laminated composite plate with multiple damaged elements. Moreover, the effect of noise on the accuracy of the proposed procedure is also investigated. The damage identification results obtained by the proposed approach are compared to those gained by the combination between modal strain energy based method and the DE. The numerical results show that regardless of the effect of noise, the proposed approach can locate and quantify the extent of damages efficiently, especially for the computational cost.

2. Damage locating using modal strain energy based method

The modal parameters of a structure, such as frequencies, mode shapes, and damping ratios are related to the damage in the structure. Therefore, the change of these modal parameters between damaged and healthy structures was used to locate damage. In addition, the change of flexibility matrix, mode shape curvature and modal strain energy established by these modal parameters is also considered as efficient indicator of damage. In the previous studies [1,37], authors proved that the change of the modal strain energy is better than the change of others in locating damage.

In this paper, the modal strain energy based method [36] using modal strain energy change ratio (MSRCR) as damage indicator is applied to identify the location of damage on laminated composite structures. The brief review of the MSECR formulation is presented as follows.

For the ith mode shape of the damaged and healthy structures, the modal strain energy (MSE) for both structures at the jth element can be calculated by

$$\mathrm{MSE}_{ij}^{h} = (\mathbf{\Phi}_i^h)^{\mathrm{T}}\mathbf{K}_j\mathbf{\Phi}_i^h, \quad \mathrm{MSE}_{ij}^{d} = (\mathbf{\Phi}_i^d)^{\mathrm{T}}\mathbf{K}_j\mathbf{\Phi}_i^d \tag{1}$$

where $\mathrm{MSE}_{ij}^{\bullet}$ is the strain energy; $\mathbf{K}_j$ is the stiffness matrix of the jth element of the healthy structure; $\mathbf{\Phi}_i^{\bullet}$ is the ith mode shape vector and the superscripts h and d denote the healthy and damaged states, respectively. The superscript T denotes the vector transpose. As pointed out in [36], Eq. (1) shows that when damage occurs in elements of a system, the MSE will change little in the undamaged elements, but there will be a larger change in the damaged elements. As a result, the modal strain energy change ratio (MSECR) was proposed to locate damaged elements. This indicator is expressed by

$$\mathrm{MSECR}_j = \frac{1}{m}\sum_{i=1}^{m}\frac{\mathrm{MSECR}_{ij}}{\mathrm{MSECR}_i^{\max}} \tag{2}$$

where

$$\mathrm{MSECR}_{ij} = \frac{|\mathrm{MSE}_{ij}^d - \mathrm{MSE}_{ij}^h|}{\mathrm{MSE}_{ij}^h} \tag{3}$$

and

$$\mathrm{MSECR}_i^{\max} = \max_k\{\mathrm{MSECR}_{ik}\} \tag{4}$$

3. Damage severity assessment

One type of damage identification methods is to transform the damage localization into an optimization problem in which the objective function is defined as the difference between the modal parameter of the damaged and healthy structures. The variables of the problem are defined as the damage severity of elements. Many kinds of objective functions have been proposed. Some typical objective functions can be mentioned as the frequency error [20], the MDLAC coefficient error (mode shape) [38] or the flexibility matrix error [39].

3.1. Objective function based on the mode shape error

In this paper, an objective function f based on the change of mode shape is defined as follows

$$f(\mathbf{x}) = \sum_{i=1}^{nm}\frac{\left\|\mathbf{\Phi}_i^d - \mathbf{\Phi}_i^h(\mathbf{x})\right\|}{\left\|\mathbf{\Phi}_i^d\right\|}, \quad x = (x_1, \ldots, x_n) \in [0,\ 1]^n \tag{5}$$

where $\mathbf{x}$ is the design variable vector corresponding with the extent of damage of n elements; $\mathbf{\Phi}_i^{\bullet}$ is the ith mode shape vector; nm is the number of modes considered; $\|\bullet\|$ is the Euclidean norm and the superscripts h and d denote the healthy and damaged states, respectively.

3.2. Differential evolution algorithm

The differential evolution (DE) algorithm [23], designed to dealing with nonlinear, non-differentiable and multimodal objective function for continuous optimization problems, has been demonstrated effectiveness and robustness by many researches for both benchmark and real-world problems [34]. In the DE, a few parameters are used and make easy implement for users. The basic procedure of the algorithm is briefly summarized via four phases as follows.

3.2.1. Initialization

Initially, a population with NP individuals is created by randomly sampling from the search space. Each individual is a vector containing D design variables $\mathbf{x}_i = \{x_{i,1}, x_{i,2}, x_{i,3}, \ldots, x_{i,D}\}$ and is produced as

$$x_{i,j} = x_j^l + \mathrm{rand}[0,1] \times (x_j^u - x_j^l) \quad i = 1,2,\ldots,NP; \quad j = 1,2,\ldots,D \tag{6}$$