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An efficient multi-stage optimization approach for damage detection in plate structures

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ABSTRACT

The paper presents an efficient multi-stage optimization approach for damage detection in plate-like structures. In this approach, the damage identification process is achieved by minimizing an objective function established via flexibility changes of the structure. The vector of design variables represents correspondingly the damage extent of elements discretized by the finite element model. For analyzing the response of plate structures, the finite element model using 9-node quadratic quadrilateral elements is applied. For solving the optimization problem, a modified differential evolution (MDE) algorithm, which can help enhance the balance of global and local searches in each generation, is used for many stages of damage detection, in which the low damage variables in each stage are gradually eliminated after several generations to reduce the dimension of searching space and to increase the convergence rate of the problem. The efficiency of the proposed method is investigated through two numerical examples for isotropic and laminated composite plates. The obtained results indicate that the proposed method not only successfully detects the location and severity of multi-damage cases in the plate structures, but also show the better efficiency in term of computational cost.

1. Introduction

As an important component of structures, plates have been widely used in many different engineering disciplines such as civil infrastructures, aerospace and automotive industries. During the service life, partial damage in plate structures caused by fatigue, aging, environmental effects and so on, can significantly reduce the level of security service and lead to catastrophic accidents due to their failure. As a result, early damage detection is very necessary not only to maintain the integrity and safety of the structure but also to minimize the maintenance cost. Hence, the development of reliable and efficient damage identification techniques for plate structures is really important, which has attracted the attention of many researchers worldwide.

In last decades, various methods based on modal data were introduced for detecting damage in plate structures, mainly based on natural frequency [1–3]; or modal strain energy [4,5]; or mode shape derivatives [6–8]; or residual force vector [9,10] or wavelet transform [11,12]. Almost these methods were extended from the original methods proposed for one-dimensional (1D) structures. Then, although they can be successfully applied for plate structures in some certain circumstance, they still possess some inherited disadvantages related to identify local damages or the damage severities.

In recent years, with the development of the computer technologies and mathematics, many optimization techniques have been developed and applied for solving variety of difficult optimization problems [13–22]. In this context, soft computing methods have also been used to predict both the location and extent of damage in plate-like structures. In this approach, researchers have presented a suitable procedure which can transform the damage diagnosis problem into an optimization problem, and then solve it by efficient optimization strategies. The main idea of this procedure is to determine the modal parameters of numerical model which can match with the measured value provided by experimental data. Some meta-heuristic optimization algorithms proposed for this approach can be listed as: Sandesh and Shankar [23] introduced a hybrid of particle swarm optimization (PSO) and genetic algorithm (GA) to identify multi-crack damages in a thin plate using an inverse time-domain formulation; Nicknam and Hosseini

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[24] presented an optimization approach called colonial competitive algorithm for localization and evaluation of damage based on changes in the natural frequencies and mode shapes of damaged plate; Amiri et al. [25] used two methods on the basis of pattern search (PS) and GA for detection and estimation of damage in plates using the modal data of damaged plate; Ding et al. [26] presented a damage detection approach using artificial bee colony (ABC) algorithm with hybrid search strategy. Although all these algorithms have generally achieved satisfactory results in solving the different damage identification problems, they are still limited to the problems with the small number of design variables which may lead to the unexpected accuracy of the damage detection. This is because the usage of all discretized finite elements of structure as design variables will lead to a very expensive computational cost. Hence, to overcome this problem, some attempts have been devoted to reducing the dimension of search space during the optimization process. For examples, Seyedpoor [27] proposed a multi-stage optimization approach based on PSO algorithm for determining the site and extent of multiple structural damages. By this approach, the healthy elements from the set of design variables will be removed after each optimization stage, and hence the effects of undamaged elements on the subsequent stage are neglected. Nouri Shirazi et al. [28] also presented an adaptive multi-stage optimization method utilizing a modified PSO for damage identification of cantilevered beam and planar truss. An operator named as Micro Search (MS) to limit the design variables by eliminating some incorrectly detected damaged elements after each several interactions can be found in references [29–31]. However, the application of these methods was still limited for structures like beam, frame and truss, and has not yet been extended for plate-like structures.

Among all evolution-based soft computing methods, the differential evolution (DE) algorithm has been received much attention. This algorithm, firstly introduced by Storn and Price [32], has been proved to be successful for numerous problems in various fields, such as mechanical engineering [18–21,33–36], pattern recognition [37], artificial neural network training [38] and so forth. Its performance can be more excellent than other existing heuristic algorithms [32,39]. Some researchers have also been applied the DE algorithm to the field of structural healthy monitoring [40–42]. Nevertheless, the application and development of this algorithm for damage identification in plate-like structures are still somewhat limited, especially in the aspect of reducing the computational cost.

Basing on the mentioned research gaps, the paper hence proposes an efficient multi-stage optimization procedure using a modified differential evolution algorithm (MS-MDE) for damage detection in plate-like structures. In this approach, the damage identification process is achieved by minimizing an objective function defined in term of the discrepancy between the flexibility matrix obtained from a modal testing on the supposed damaged structure and the corresponding one obtained by a numerical model. The vector of design variables represents correspondingly the damage extent of elements discretized by the finite element model. For analyzing the response of plate structures, the finite element model using 9-node quadratic quadrilateral elements is applied. For solving the optimization problem, a modified differential evolution (MDE) algorithm by Ho-Huu et al. [36], which can help enhance the balance of global and local searches in each generation, is used for many stages of damage detection, in which the low damage variables in each stage are gradually eliminated after several generations to reduce the dimension of searching space and to increase the convergence rate of the problem. To investigate the efficiency of the proposed multi-stage damage detection method, an extensive numerical study is conducted for both isotropic and composite laminated plates. Moreover, the effect of noise on the accuracy of the proposed method is also investigated.

The rest of this paper is organized as follows. Section 2 describes the formulation of damage prediction as an optimization problem. Section 3 introduces the modified version of the DE algorithm and a multi-stage optimization approach via the MDE algorithm. The obtained numerical results are discussed in Section 4. Finally, the main conclusions are withdrawn in Section 5.

2. Formulation for structural damage identification

This section is devoted to briefly introduce the foundation of damage identification problem including damage modeling, an objective function based on modal flexibility and measurement noise.

2.1. Damage modeling

The modal characteristic of an intact structure is expressed by the following eigenvalue equation

$$\left(\mathbf{K} - \omega_i^2\mathbf{M}\right)\mathbf{\Phi}_i = \mathbf{0}\ , \quad i = (1,\ 2,\ \dots, n) \tag{1}$$

where $\mathbf{K}$ and $\mathbf{M}$ are stiffness and mass matrices with the dimension of $(n \times n)$; ω_i and $\mathbf{\Phi}_i$ are the ith natural frequency and mode shape, respectively; and n is the number of degrees of freedom.

In the literature, a damaged plate structure can be modeled by different approaches [43–49] which are usually presented as a cracked model. These approaches lead to increase the complexity of simulation which is usually not effective for analyzing the structural response used in optimization problems. Hence, for simplicity of simulating the damage of elements in the structure used in optimization problems, a popular approach is to reduce the stiffness of the damaged elements. This damage model agrees with many previous studies [4,7,10], and hence it is used in the present work. If we assume that damage ratio of the eth element is a_e, the global stiffness matrix of the structure will be expressed as summation of undamaged and damaged stiffness matrices and can be written as

$$\mathbf{K} = \sum_{e=1}^{Ne} (1 - a_e)\mathbf{K}_e \tag{2}$$

where $\mathbf{K}_e$ is the stiffness matrix of the eth element; Ne is the number of elements and $a_e \in [0,\ 1]$ show the damage extent of elements, in which 0 implies healthy element and 1 means the completely damaged element.

2.2. Objective function based on modal flexibility

It is well known that damage reduces the stiffness and leads to increase the flexibility of the structure. Hence, any change observed in the flexibility matrix can be interpreted as damage indication in the structure and further information on the damage location and its extent [50]. In the previous studies [51–53], authors concluded that the advantage of using flexibility matrix is better than those using others in damage diagnose.

In the damage detection approach by finding the solution of an optimization problem, structural damage identification can be obtained by minimizing an objective function defined as difference between the measured vibration data and the analytical data. Within this context, a suitable choice of the cost function is very important because it can significantly influence the performance of the utilized optimization algorithm. Thus, in this study, the difference between the flexibility matrix obtained from a testing modal and the corresponding one obtained from a numerical model is considered as an objective function for damage assessment in plate structures, and can be written in the form of

$$f(\mathbf{x}) = \frac{\left\|\mathbf{F}^{exp} - \mathbf{F}^{ana}(\mathbf{x})\right\|_{Fro}^{p}}{p\left\|\mathbf{F}^{exp}\right\|_{Fro}^{p}}\ , \qquad \mathbf{x} = (x_1, \dots, x_n) \in [0,\ 1]^n \tag{3}$$