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Structural damage detection using artificial bee colony algorithm with hybrid search strategy

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ABSTRACT

An approach for structural damage detection using the artificial bee colony (ABC) algorithm with hybrid search strategy based on modal data is presented. More search strategies are offered and the bee will choose one search mode based on the tournament selection strategy. And a kind of elimination mechanism is introduced to improve the convergence rate. A truss and a plate are studied as two numerical examples to illustrate the efficiency of proposed method. An experimental work on a beam is studied for further verification. Final results show the present method can acquire the better identification results, compared with those from GA, the original ABC and quick ABC (QABC) algorithm, even under some measurement noise.

1. Introduction

Structural damage in normal service may contain fatigue, corrosion and aging, or it may be produced by earthquake, impact loads, wind etc., early damage identification allows maintenance and repair works to be properly programmed and thus minimizing the maintenance costs.

Many researchers have presented methods for damage identification using natural frequencies and mode shapes, mainly including the sensitivity methods [1–3], modal residual methods [4,5], wavelet transform methods [6,7], modal force error methods [8,9] and optimization methods [10]. More recently, Irwanda et al. [11] also discussed the temperature's influence to the damage identification. Malekzadeh et al. [12] proposed a damage estimation problem based on the multivariate statistic algorithm, and delivered promising results to detect both local and local damage implemented on the bridge structure. Malekzadeh et al. [13] also posed a hybrid data interpretation frame work for the long-term performance assessment of structures by integrating two data analysis approaches: parametric (model-based, physics-based) and non-parametric (data-driven, model-free) approaches.

In the damage identification of structures, the damage parameters are generally related to the stiffness as discussed by Araujo dos Santos et al. [14] and Chen and Bicanic [15]. When discretizing the structure into a number of finite elements, the stiffness distribution in the structures is expressed in terms of the stiffness parameters. One of the main difficulties in identifying the stiffness parameters lies in the large number of unknowns. When solving an inverse problem of parameter identification, it is usually formulated as an objective function of a weighted sum of squared difference between the measured value and the corresponding simulated value of the dynamic properties of the structures. The inverse reconstruction can then be solved by minimizing the objective function. Meta-heuristic algorithms have been widely used as a searching technique for solving such nonlinear problem. Compared with the traditional methods [1–6], the advantages of heuristic algorithms lie in, (a) they do not need the sensitivity analysis and initial guess [16]; and (b) they converge to the global optimum solution. Among all the heuristic algorithms, genetic algorithm (GA), particle swarm optimization (PSO), ant colony optimization (ACO), artificial neural networks (ANN), evolutionary strategy (ES), and differential evolution (DE) algorithms have gained increasing attention. Gökdağ and Yildiz [17,18] utilized the modal flexibility and PSO algorithm to detect the local damage, while Gökdağ [19] also introduced the beam type structures under moving vehicle, objective function is defined based on the difference of damaged beam dynamic response and the response calculated by the mathematical model of the beam, then used PSO to identify the crack parameters. Friswell et al. [20] proposed a combined genetic and eigensensitivity method to identify a linear structure. Tsou and Shen [21] applied natural frequencies and residual vector change as the input of BP network for structural damage detection. Li et al. [22] presented a symbolization-based DE strategy to estimate structural system parameters with and

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without noise pollution. Dackermann et al. [23] used cepstrum and ANN procedure to realize parameter identification of structural relying on response-only measurements. Janfarkhani and Masri [24] exhibited a good parameter estimation result based on finite element model updating using ES for structural damage detection. All these methods have generally achieved satisfactory results in solving the damage identification problem.

Apart from the above mentioned heuristic algorithms, artificial bee colony (ABC) algorithm is aroused much attention. This algorithm is motivated by the intelligent behavior of honey bees when seeking a high quality food source. ABC is a population based stochastic algorithm with implementation simplicity since the common control parameters are colony size (CS), the maximum iteration step, limit. It has the advantage of simple structure (as simple as PSO and DE), ease of use, and high stability. Karaboga and Basturk [25] adopted it to optimize multivariable functions and compared their results with those produced by GA, PSO, DE and particle swarm inspired evolutionary algorithm (PS-EA). Other studies have also compared the performance of ABC with other existing heuristic algorithms [26], and the outcomes reported in the literature suggest that ABC can be more excellent than other methods in some optimization problems [27]. Since this algorithm has been proven to be successful in dealing with optimization problems, several researches have applied it to solve actual problems. Bouaziz et al. [28] utilized ABC algorithm for multilevel thresholding of iris images. Agrawal and Sahu [29] used ABC algorithm to design two-channel quadrature mirror filter banks. Sonmez [30,31] also used the ABC algorithm together with a penalty function method to minimize the weight of truss structure. Eom and Han [32] introduced the ABC algorithm to the field of topology optimization of nonlinear structure. A hybrid method based on ABC algorithm and Nelder–Mead simplex method was proposed by Kang et al. [33] and applied to parameter identification of concrete dam-foundation systems. Omkar [34] applied the ABC algorithm for design of composite structures from a multi-objective optimization procedure. However, only a few works have been reported to the field of damage identification. Sun et al. [35] utilized the ABC algorithm with a nonlinear factor to enhance the balance of global and local searches to realize the structural identification using time domain response. Sun and Raimondo [36] also used the ABC algorithm combined with Nelder–Mead simplex method to detect damages in building models.

The paper mainly deals with the damage detection problem using ABC algorithm with hybrid search strategy based on an objective function established in frequency domain. Section 2 describes the formulation of damage identification as an optimization problem. Section 3 presents a modified version of ABC algorithm which is suitable for structural damage identification. Section 4 discusses the results of the numerical simulations and experimental work. In Section 5, we present the discussions, and the conclusion is made in Section 6.

2. Mathematical model

2.1. Parameterization of damage

The modal characteristics of an undamaged structure are described by the eigenvalue equation

$$(\mathbf{K}-\omega_i^2\mathbf{M})\cdot\mathbf{\Phi_i}=0 \tag{1}$$

where $\mathbf{K}$ and $\mathbf{M}$ are the global stiffness and mass matrices, respectively. ω_i is the ith natural frequency and is the corresponding mode shape.

According to continuum damage mechanics, damage can be expressed through a scalar variable α_i with value between 0 and 1 [37]. $\alpha_i=0$ represents the ith element is intact while $\alpha_i=1$ indicates that it is completely damaged. The global stiffness matrix $\mathbf{K_d}$ of the damaged structure can be expressed by damage parameters

$$\mathbf{K_d}=\sum_{i=1}^{nel}(1-\alpha_i)\cdot\mathbf{K_{ei}} \tag{2}$$

where $\mathbf{K_{ei}}$ denotes the ith elemental stiffness matrix, nel denotes the total number of finite element.

2.2. Objective function based on the vibration data

The observation that changes in structural properties cause changes in vibration frequencies and mode shapes is the impetus for using modal methods for damage identification and health monitoring. The objective function based on both natural frequency and Modal Assurance Criteria (MAC) can be expressed as

$$f=\sum_{i=1}^{NF} w_{\omega i}\Delta\omega_i^2+\sum_{i=1}^{NM} w_{\Phi i}\cdot(1-MAC_i) \tag{3}$$

in which

$$\Delta\omega_i=\frac{|\omega_i^c-\omega_i^m|}{\omega_i^m} \tag{4}$$

$$MAC_i=\frac{(\mathbf{\Phi_i^{cT}}\cdot\mathbf{\Phi_i^m})^2}{||\mathbf{\Phi_i^c}||^2||\mathbf{\Phi_i^m}||^2} \tag{5}$$

where $w_{\omega i}$ is a weight factor corresponding to the ith natural frequency, while $w_{\Phi i}$ corresponding to ith MAC. $\mathbf{\Phi_i^c}$ and $\mathbf{\Phi_i^m}$ are the ith calculated and measured mode shapes. NF and NM are the numbers of frequencies and mode shapes used in calculation, respectively. It should be pointed out that the calculated natural frequency ω_i^c and mode shape $\mathbf{\Phi_i^c}$ are related to damage parameters $[\alpha_1,\alpha_2,...,\alpha_{nel}]$. In the inverse problem, the damage vector is identified to indicate the damage extent of structure.

3. Algorithm for damage identification

3.1. Introduction to the artificial bee colony algorithm

The bees colony are divided in three groups when they commence to find food. The first group contains employed bees. These bees have a food source position in their mind when they leave from the hive and they share the information (including the quality and quantity about the food resource) on the dancing area in the hive. Some of the bees watch the dances of the employed bees and then decide the food source to exploit. This group of the bees named onlookers. In the algorithm, onlookers select the food sources in a probability that corresponding to the qualities of the food sources. After onlookers choosing the food source, then they will become the employed bees, going to the selected food source and exploiting the better source in the neighborhood around the destination. If they find a better place, they will give up the primary selected place ("greedy selection rule"). The last bee group is called scout bees. Regardless of any information of other bees, a scout finds a new food source and start to consume it, then it continues its work as an employed bee. Hence, while the known resources are consuming, at the same time exploration of the new food sources is provided. At the beginning of the search (initialization phase), all employed bees start with random food sources, in further cycles, when the food sources are abandoned, the employed bee related to the abandoned resource becomes a scout. In the algorithm, a parameter, *limit* is used to control the abandonment problem of the food sources. For every solution, the trial number of improvement is taken, in each cycle of the solution which has the maximum trial number and its trial number is compared with the parameter *limit*. If the *limit* value is reached,