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Bird mating optimizer for structural damage detection using a hybrid objective function

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ABSTRACT

A structural damage detection approach based on bird mating optimizer (BMO) in time-frequency domain is proposed in this paper. A hybrid objective function is introduced by minimizing the discrepancies between the measured and calculated natural frequencies and correlation function vector of acceleration of damaged and intact structures. Then the BMO algorithm with a disturbance procedure is developed to solve the objective function. Benefited from the hybrid objective function, only a few number of natural frequencies are needed in the detection process. And the disturbance procedure designed in this paper can enhance the precision of identification. The efficiency and robustness of the proposed method are verified by a planar truss and a frame, a three connected shear buildings and an experimental work. The studies in numerical simulations validate that the proposed objective function and disturbance procedure are helpful to improve the precision of identification. The experimental work shows that the proposed method has the potential of practical application. In addition, comparison among the proposed method and other optimization algorithms, i.e. GA, ABC, L-SHADE and HCLPSO, reveals the superiority of the proposed method in structural damage detection.

1. Introduction

Generally it is impossible for a structure to be not liable of failure. Almost all of the load-carrying structures will gradually accumulate local damages with time in their components and thus may lead to disastrous failure of the structure. Therefore, it is necessary to identify the damage accurately and effectively in time to assure the safety of structures.

In the last few decades, vibration-based approaches for damage identification have been studied extensively by many researchers in frequency domain. For example, Cawley and Adams [1] and Narkis [2] localized the structural damage by measuring the natural frequencies. Pandey et al. [3] identified the local damage by observing the changes in curvature mode shapes. Other approaches using mode shapes were reported in Ref. [4,5]. Later Pandey, Biswas and other researchers [6–8] made use of the flexibility in damage detection. Chatterjee [9] developed the higher order frequency response functions (FRFs) to identify the damage in cantilever beam with breathing crack. Similarly a frequency response-based method was developed by Hwang and Kim [10] to improve the detected feasibility by reducing the number of measured vectors from the full set of FRFs. Shi and Law [11] proposed the modal strain energy ratio for damage localization. More recently an experimental work was done by Lee et al. [12] to identify the cracks on a steel truss. In their work a localization index was utilized first, and the modal data were adopted for model updating.

On the other hand, approaches for damage identification in time domain have been developed rapidly in recent years. Cattatius and Inman [13] proposed a non-destructive time domain approach to identify the local structural damage. By observing the features of dynamic response sensitivity, Lu and Law [14–16] proposed a response sensitivity-based method to identify the structural damages. This method can effectively identify both the damage location and severity through the finite element model updating. More recently making use of both time-domain and frequency-domain data a hybrid damage detection method using dynamic-reduction transformation matrix and modal force error was studied by Mousavia and Gandomi [17]. In order to reduce the power budget of the self-powered sensors, approaches for damage detection using binary data is studied by Salehi et al. [18,19].

However a challenge still exists in the methods mentioned above: the conventional model-based damage identification methods usually are gradient based and tend to reach a local minimum when solving the nonlinear objective functions. In recent years, researchers have paid

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more attentions to the evolution algorithms and machine learning technique. For instance, Wu et al. [20] were among the very early ones who use Neural Network (NN) for damage detection. A back-propagation algorithm was employed in their study. Then other improvement of NN was developed for damage detection in Refs. [21,22]. Genetic Algorithm (GA) is another choice as an optimization tool. A localization and quantification approach based on GA was proposed by Mares and Surace [23] using the residual force method. Maity and Tripathy [24] used GA to identify the structural damage from changes in natural frequencies. Sahoo et al. [25] introduced a hybrid neuro genetic algorithm to assess the structural damage. Recently some new optimization algorithms, such as ant colony optimization (ACO) [26–28] and particle swarm optimization (PSO) [29,30], have been employed in damage detection. For example Mohan et al. [31] used the FRF to detect structural damage by employing PSO. Kang et al. [32] improved the PSO by an artificial immune system, and employed it in the damage detection. A two-stage method for structural damage detection using PSO was proposed by Seyedpoor [33]. In this study, damage location is predicted by modal strain energy based index, and then the damage extent is obtained through the PSO. More recently an approach for structural damage detection based on artificial bee colony algorithm was developed by Ding et al. [34]. A Kernel-based approach was studied by Satos et al. [35] for damage detection under varying operational and environmental conditions. For discrete size optimization of steel trusses, several algorithm including guided stochastic search technique, elitist self-adaptive step-size search and big bang-big crunch algorithm was investigated by Azad et al. [36–38].

A novel evolution algorithm named bird mating optimizer (BMO) was proposed by Askarzadeh [39–41] more recently. It is a population-based optimization algorithm which employs the mating process of birds as a framework. The BMO was utilized to extract maximum power of solar cells by Askarzadeh and Rezazadeh [40]. And an artificial neural network training using BMO was established in [41]. The studies of Askarzadeh show that BMO is an efficient algorithm for multimodal optimization, and it is a promising algorithm for structural damage identification.

In this paper a structural local damage detection method based on BMO is proposed. A hybrid objective function is established by minimizing the discrepancies between the measured natural frequencies in combination with MAC of correlation function vector of acceleration of damaged and intact structures. Only the first few natural frequencies and several acceleration measurements are used for damage identification. It is unnecessary to carry out modal test and modal analysis in the damage detection process, thus it is very convenient and promising for practical applications. In this study, a disturbance procedure is proposed to improve the accuracy of the identification results. Several structures, i.e. a planar truss, a planar frame, and a complex shear building system are utilized to verify the effectiveness of the proposed approach. The influences of the measurement noises and measured points are also studied in the simulations. The identified results show that the proposed method is robust and efficient. Meanwhile the superiority of the designed hybrid objective function and disturbance procedure is validated in the simulations. In addition comparison among the proposed method and GA, ABC, L-SHADE, HCLPSO is conducted to validate the selection of BMO in damage detection. At last a set of experimental data is utilized to illustrate the potential of practical application of the proposed approach.

2. Methodology for damage detection

2.1. Modeling structural local damage

It is well known that the eigenvalue equation and the dynamic equation of a structure can be obtained from the general finite element model as follows,

$$(\mathbf{K} - \omega_j^2\mathbf{M})\phi_j = 0 \tag{1}$$

$$\mathbf{M}\ddot{\mathbf{d}} + \mathbf{C}\dot{\mathbf{d}} + \mathbf{K}\mathbf{d} = \mathbf{F}(t) \tag{2}$$

where $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ are the system mass, damping and stiffness matrices, respectively. ω_j is the$j$th natural frequency and ϕ_j is the corresponding mode shape. Rayleigh damping model is adopted here, and the damping matrix can be calculated by $\mathbf{C} = a_1\mathbf{M} + a_2\mathbf{K}$, where a_1 and a_2 are constants to be determined from two modal damping ratios.

Neglecting the effect of local damages on the mass property of the structure, fatigue damages decrease the material module of elasticity. This will, consequently, degrade the stiffness of damaged element [42]. Therefore it is usually assumed that local damage only leads to the loss in structural stiffness. When a structure with nel elements is damaged, the reduction of the stiffness can be evaluated by a set of damage parametersα_i $(i = 1,\ 2,\dots,\ nel)$. The value range of parameter α_i is between 0 and 1. $\alpha_i = 1$ corresponds to that the ith element is intact while $\alpha_i = 0$ represents that it is completely damaged. Therefore the stiffness matrix of the damaged structure can be written as

$$\mathbf{K_d} = \sum_{i=1}^{nel} \alpha_i \mathbf{k_i^e} \tag{3}$$

where $\mathbf{K_d}$ is the stiffness matrix of the damaged system, and $\mathbf{k_i^e}$ presents the ith elemental stiffness matrix in the global form. Based on this damage model, damage identification implies to identify each value in the damage parameter vector $\{\alpha\}$.

2.2. Objective function for damage detection

In the context of vibration-based damage detection the task is to minimize the differences between the measured response data and the calculated ones. In this study, we make use of the modal frequencies and acceleration history to establish the objective function.

Based on the assumed damage model, Eq. (1) indicates that the changes of stiffness will influence the structural properties in frequency domain, such as natural frequencies and mode shapes. In practice, the natural frequencies of the structures can be identified from the recorded time history of the structural dynamic responses accurately, while the corresponding full scale mode shapes are relatively difficult to be obtained by limited number of measured points, especially the higher ones. Generally speaking, only a few number of lower modal parameters can be identified with confidence for a real structure. Therefore only changes in the first few natural frequencies are used in the objective function in frequency domain,

$$\Delta\omega_j = \left| \frac{\omega_j^C - \omega_j^M}{\omega_j^M} \right| \tag{4}$$

where ω_j^C and ω_j^M are the jth calculated and measured natural frequencies, respectively.

On the other hand local damage can also lead to the changes in structural dynamic responses when the excitation remains unchanged. As one of the features about time domain information, correlation functions of the acceleration responses will be changed once the structure is damaged. Therefore the changes of correlation functions of the structural acceleration responses are also included in the objective function for structural damage identification in this study.

In signal analysis the general correlation function of the given discrete time series $x(n)$ and $y(n)$can be expressed as,

$$R_{xy}(m) = E[x(n)y(n+m)] = \lim_{N\to\infty} \frac{1}{N} \sum_{n=0}^{N-1} x(n)y(n+m) \tag{5}$$

According to Eq. (5) a correlation function vector (CorV) can be assembled from the discrete value of the correlation function $R_{xy}(m)$ as follows,