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A two-stage method to identify structural damage sites and extents by using evidence theory and micro-search genetic algorithm

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ABSTRACT

A two-stage method of determining the location and extent of multiple structural damages by using information fusion technique and genetic algorithm is presented in this paper. First the damage detection strategy is to localize the damage sites by using an evidence theory, which can perfectly integrate the damage identification information coming from both natural frequencies and mode shapes. Then, a micro-search genetic algorithm (MSGA) is proposed to determine the damage extent. A cantilever beam is analyzed as a numerical example to compare the performance of the proposed method with the multiple damage location assurance criterions (MDLAC) and the simple genetic algorithms. Simulation results show that identification results of the evidence theory are better than those both of the frequency MDLAC method and the mode shape MDLAC method, and the MSGA is also more accurate and effective than the simple genetic algorithms. Therefore, the two-stage method is very effective for the identification of multiple structural damages.

1. Introduction

In recent years, many methods have been developed to detect the location and extent of damage by using the changes in their modal parameters. Natural frequencies and mode shapes are the most popular parameters used in the identification. Cawley and Adams [1] used the changes in the natural frequencies together with a finite element model to locate the damage site. Salawu [2] had an overview about structural damage detection methods which used frequency data. Chaudhari and Maiti [3] and Chinchalkar [4] described a numerical method for determining the location of a crack in a beam of varying depth when the lowest three natural frequencies of the cracked beam are known. Allemang and Brown [5] proposed a modal assurance criterion (MAC), which is a simple quantitative method for comparing mode shapes. Pindey and Biswas [6] used complete mode shapes for the damaged and undamaged states to identify both the location and amount of damage by solving a system of linear equations. These methods can perfectly identify single damage location, but they are not very effective to detect multiple damage locations. Moreover, these methods only used one kind of vibration parameters, natural frequencies or mode shapes.

Genetic algorithm (GA) is an effective search method, and it has been applied to the problem of multiple structural damage identification. Mares and Surace [7] used GA to adjust the structural parameters to minimize the equation error (residual force) to locate and identify structural damage from measured natural frequencies or mode shapes. The initial population in that study was not random but defined heuristically to represent the undamaged structure. Friswell et al. [8]

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used genetic and eigensensitivity algorithms to identify the location and extent of structural damage, respectively, by minimizing the output error for natural frequencies. Yi et al. [9] proposed a multi-variable crossover genetic algorithm (MVCGA) to detect multiple damages. Chou and Ghaboussi [10] used GA with incompletely measured static displacements to determine the location and extent of structural damage. However, the identification efficiency of these methods is not very high.

In this paper, a two-stage method is presented to solve these problems. First, an information fusion method (evidence theory) is applied to detect multiple structural damage sites. The information fusion method can combine data from multiple information sources and related information from associated databases, to achieve improved accuracies and more specific inferences than could be achieved by the use of a single source alone. Here, we use the evidence theory to integrate both frequency identification information and mode shape identification information. Thus, the suspected damage element sites can be effectively localized using the combination information. GA will be further used to determine the true sites and extent of damage after the suspected damaged elements have been found.

2. Damage localization

Here, the damage localization method is simply described as follows: First, the frequency changes and the mode shape changes are regarded as two different information sources. And two different damage detection methods, i.e. the frequency MDLAC method and the mode shape MDLAC method, are applied to acquire local damage decisions, respectively. Then these local damage decisions are sent to a fusion center. In the fusion center, the evidence theory is used to obtain a global decision.

2.1. Localization using frequency changes

Messina et al. [11] presented the sensitivity- and statistical-based method called the multiple damage location assurance criterion (MDLAC) to localize structural damage. It is similar to the modal assurance criterion (MAC) used for comparing mode shape vectors, which is defined as

$$MDLAC_f(\{\delta D_j\}) = \frac{|\{\Delta f\}^T\{\delta f(\{\delta D_j\})\}|^2}{(\{\Delta f\}^T\{\Delta f\})(\delta f(\{\delta D_j\})^T\delta f(\{\delta D_j\}))} \tag{1}$$

where $\{\Delta f\}$ is the measured frequency change vector and $\{\delta f\}$ is the theoretical frequency change vector for damage on a known size $\{\delta D_j\}$ at location j. The size of $\{\delta f\}$ is equal to the number of modes used, while the size of $\{\delta D_j\}$ is equal to the number of potential damaged sites under consideration. The sensitivity of the kth natural frequency to damage at location j is given by [11]

$$\frac{\partial f_k}{\partial D_j} = \frac{1}{8f_k^0\pi^2}\frac{\{\Phi_k\}^T[K_j]\{\Phi_k\}}{\{\Phi_k\}^T[M]\{\Phi_k\}} \tag{2}$$

where $[K_j]$ is the stiffness matrix of the jth element positioned within the global matrix, $[M]$ is the global mass matrix and $\{\Phi_k\}$ is the kth mode shape vector; all terms evaluated are for the undamaged structure.

The frequency MDLAC values will be further converted into probability values. Each of the MDLAC values is divided by the sum of all MDLAC values in turn. Thus, it normalizes the sum to one. The change makes preparations for the following information fusion and the acquired probability values can be regarded as information source data.

2.2. Localization using mode shape changes

Shi et al. [12] utilized incomplete mode shape changes to identify damage sites, and his method is also called MDLAC, which is similar to Messina's method. The MDLAC is formulated as

$$MDLAC_m(\{\delta D_j\}) = \frac{|\{\Delta\Phi\}^T\{\delta\Phi(\{\delta D_j\})\}|^2}{(\{\Delta\Phi\}^T\{\Delta\Phi\})(\delta\Phi(\{\delta D_j\})^T\delta\Phi(\{\delta D_j\}))} \tag{3}$$

where $\{\Delta\Phi\}$ is the measured mode shape change vector with a dimension equal to the product of the number of measured modes and the number of sensor location; and $\{\delta\Phi\}$ is the analytical mode shape change at the same DOFs for damage of a known size $\{\delta D_j\}$ at different location j. The sensitivity of the kth mode shape to damage at element j is given by [12]

$$\frac{\partial\{\Phi_k\}}{\partial D_j} = \sum_{r=1}^{n^*}\frac{-\{\Phi_r\}^T[K_j]\{\Phi_k\}}{\lambda_r-\lambda_k}\{\Phi_r\} \quad (r\neq k) \tag{4}$$

in which $\{\Phi_k\}$ and λ_k are the kth analytical mode shape and eigenvalue, respectively; and n^* is the number of analytical modes used in the calculation. When m modes are used together to localize the damage sites, the mode shape change