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The Differential Evolution method applied to continuum damage identification via flexibility matrix

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ABSTRACT

In the present work, a structural damage identification approach, built on the flexibility matrix, is proposed. Here, the damage state of the structure is continuously described by a cohesion parameter, which, in turn, is spatially discretized by the finite element method. Then, the inverse problem of damage identification is defined as an optimization one, where the objective is to minimize, with respect to the nodal cohesion parameters, a functional based on the difference between the experimentally obtained flexibility matrix and the corresponding one predicted by a finite element model of the structure. The Differential Evolution stochastic optimization method was considered for solving the resulting damage identification problem. The assessment of the proposed approach has been performed by means of numerical simulations on a simply supported Euler–Bernoulli beam. A brief analysis of the influence of different damage positions and severities on the undamped natural frequencies and on the flexibility matrix of the structure is presented. Then, the influence of damage and different levels of noise on the mode shapes of the structure is also considered. In the damage identification problem, different damage scenarios and noise levels were addressed. For comparison purposes, other stochastic optimization methods, namely, Particle Swarm Optimization, Luus–Jaakola and Simulated Annealing, were also considered for the identification of one damage scenario in the presence of noise corrupted data.

1. Introduction

Structural damage identification and health monitoring are essential issues for determining safety reliability and remaining lifetime of aerospace, civil and mechanical structures. The technological and scientific challenges posed by damage identification problems yielded a great research activity on this subject within the scientific community [1]. Although different damage identification approaches are proposed in the specialized literature, one may observe a special attention to the nondestructive ones built on the dynamic behavior of the structures. These ones, encompassing deterministic [2] or statistical perspectives [3,4], consider different types of data (modal parameters [5,6], time series [7], frequency responses [8]) and distinct mathematical formulations and numerical algorithms for solving the corresponding inverse problem [9,10].

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Most of the proposed structural damage identification approaches considers the traditional modal analysis and is built on the general framework of Finite Element Model (FEM) updating [11]. The basic idea of the vibration based damage identification approaches is that the modal properties of the structure (frequencies, mode shapes and modal damping) are functions of the physical ones (mass, stiffness and damping) and, therefore, changes in the physical properties, due to damage, will be reflected in the modal characteristics, which can be measured and used to infer the damage. Hence, the damage identification problem is defined as an optimization one and a set of parameters, supposed to describe the damage scenario, is sought in order to minimize an arbitrary error function, which is defined as the difference between some outputs or matrices of the FEM of the structure and the corresponding ones obtained from a modal testing on the supposed damaged structure. When considering the modal properties of the structure or quantities derived from them, the inverse problem of damage identification may be defined, for instance, based on the undamped natural frequencies [12], undamped natural frequencies and mode shapes [13], mode shapes curvatures [14,15], modal strain energy [16,17] or the flexibility matrix [18,19].

Damage identification fits the broad category of inverse problems and, in general, it is ill-posed and ill-conditioned. Conventional optimization methods are gradient-based deterministic ones, whose convergence may depend on a good initial guess of the structural damage state and the solution may represent only a local minimum of the functional. In order to circumvent these inherent difficulties of the conventional optimization methods, one may consider regularization terms [20] or stochastic methods. In recent years, among other methods, the Differential Evolution, Particle Swarm Optimization, Luus–Jaakola and Simulated Annealing, which are considered in the present work, have been succeeded in solving different damage identification problems [21–23].

In the present work, the damage state of the structure is continuously described by a cohesion parameter. The cohesion field is discretized by the finite element method and this spatial discretization is not necessarily coincident with that used for the displacement field. Therefore, the damage model adopted in the present work is different from that commonly adopted in the specialized literature, where the damage is supposed to be constant within a finite element of the structure. The damage identification problem is, then, built on the flexibility matrix of the studied structure. The corresponding inverse problem of damage identification is defined as a minimization one, where the aim is to find the vector of nodal cohesion parameters that minimizes the squared norm of the difference between the flexibility matrix obtained from a modal test on the supposed damaged structure and the corresponding one predicted by a finite element model. The Differential Evolution stochastic method is considered to solve the resulting nonlinear optimization problem.

The remainder of the paper is organized as follows. Section 2 presents all the mathematical formulation required for the definition of the inverse problem of continuum damage identification built on the flexibility matrix. Hence, the continuum damage model, the flexibility matrix as a function of the modal properties of the structure and the formulation of the damage identification problem are presented in this section. Section 3 presents the Differential Evolution stochastic optimization method. Section 4 presents the numerical assessment of the potentiality of the proposed damage identification approach applied on a simply supported Euler–Bernoulli beam. First, a brief analysis of the influence of damage and noise on the undamped natural frequencies and on the flexibility matrix of the structure is presented. Then, the Differential Evolution method is considered for solving the damage identification problem for different damage scenarios and for the synthetic experimental data corrupted with different levels of additive noise. A performance comparison encompassing the Differential Evolution method and other stochastic optimization methods is also presented in this section. Section 5 presents the concluding remarks and Appendix A presents a description of the other optimization methods also considered in the present work, namely, Particle Swarm Optimization, Luus–Jaakola and Simulated Annealing.

2. Mathematical modeling

This section is devoted to present the fundamentals of the flexibility based continuum damage identification approach considered in the present work.

2.1. Continuum damage model

In the present damage identification approach, the damage state of the structure is continuously described by a structural parameter $\beta \in [0, 1]$, named *cohesion parameter* [19]. This parameter is related with the connections among material points and can be interpreted as a measure of the local cohesion state of the material. If $\beta = 1$, it is assumed that all connections between the material points are preserved and, therefore, there is no damage in the structure. If $\beta = 0$, a local rupture is considered, since all connections between the material points are broken.

In the present work, it is assumed that, during the vibration test, the internal forces within the structure do not suffice to cause the continuation of the damage process and, besides, that the damage affects only the elastic properties of the structure. Hence, for the special case of an Euler–Bernoulli beam, the stiffness matrix of a finite element is given by

$$\mathbf{K}^e = \int_0^{l_e} \beta^e(x) E_0 I_0 \frac{\partial^2 \mathbf{N}^e(x)}{\partial x^2} \frac{\partial^2 \mathbf{N}^e(x)^T}{\partial x^2} \, \mathrm{d}x \tag{1}$$