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Structural single and multiple crack detection in cantilever beams using a hybrid Cuckoo-Nelder-Mead optimization method

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In this study, the number, location and depth of cracks created in several Euler-Bernoulli beams, such as a simple beam and a more complex multi-step beam are investigated. The location and depth of the created cracks are determined using the hybrid Cuckoo-Nelder-Mead Optimization Algorithm (COA-NM) with high accuracy. The natural frequencies of the cracked beams are determined by solving frequency response equations, and performing modal test experiments. Results of COA-NM show a higher accuracy and convergence speed compared with other methods such as GA-NM, PSO-NM, GA, PSO, COA and several previous studies. Amount of calculations performed by COA-NM to achieve this accuracy is much less compared to other methods.

1. Introduction

In recent decades, vibration-based non-destructive tests have gained many applications in detecting structural defects, because they are non-destructive, fast, cheap and comprehensive. Nowadays, these methods are frequently used in detecting and measuring parameters of a crack created in different structures, as one of the most common structural defects. Among all, the existence of cracks in beams are considered more often, due to diversity of forces applied to them compared to other structural elements; Furthermore, beams are simple and widely used in many engineering structures, such as buildings. Therefore, such cracks should be identified before they propagate and endanger the entire structure. It is known that existence of a crack leads to a decrease in natural frequency and a change in mode shape of the structure [1]. Using natural frequency data obtained by vibration-based non-destructive methods, such as modal analysis, the parameters of a detected crack (including location and depth) in a structure may be identified.

Crack detection in beam structures has been widely addressed in the literature. Dimarogonas [2] and Chondros and Dimarogonas [3] modeled a crack as a local flexibility by using fracture mechanics methods. They developed a spectral method in order to identify cracks in various structures relating the crack depth to the change of natural frequencies.

Lee [4] solved the problem of the cracked beam using the Finite Element Method (FEM) and the Newton-Raphson method. Patil and Maiti [5] used Transfer Matrix Method (TMM) to find the bending natural frequencies of the cracked beam. Rosales et al. [6] proposed a method to solve the inverse problem of crack detection. In their study, they combined power series with

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the neural network. The existence of multiple transverse cracks in the beam leads to further complicated dynamic response of the beam compared with the beam with single transverse crack [7]. Due to the possibility of the occurrence of multiple cracks in the elements of engineering structures such as beams and their possibility of being destroyed faster, several researches have been done on multiple-cracked beams recently [8–12]. In his research, Sekhar studied structures with multiple cracks, such as beams, rotors and pipes. He published his findings in [9]. Detection of such cracks (i.e., multiple cracks) in more complex beams is a fascinating subject that has recently attracted the attention of researchers. Zhang et al. [13] studied crack detection in a stepped cantilever beam by combining TMM and wavelet analysis method. They first detected the location of crack using peak of wavelet coefficients and then found the crack depth using TMM. Nandwana and Maiti [14] focused on crack detection in stepped beam with single transverse crack. They modeled the crack with a torsional spring and drew three graphs for each of the three natural frequencies. The intersection of three graphs identified the location of the crack. Maghsoodi et al. [7] investigated the detection of multiple cracks in a multi-stepped beam using energy method and an analytic strategy based on Rayleigh-Ritz method.

Since both location and size of a crack affect natural frequencies of a cracked beam, most vibration-based methods require a two-step procedure to estimate crack location and depth. Considering crack detection as an optimization problem, different parameters may be selected as design variables, such as location and size of the cracks [15]. Recently, damage detection via optimization techniques has increased significantly.

Vakil-Baghmisheh et al. [16] estimated depth and location of a created crack using genetic optimization method. Utilizing the Modified Cuckoo Optimization Algorithm (MCOA), Moezi et al. [17] estimated very accurately the depth and location of an open-edge crack created in a beam. They compared their proposed method with Cuckoo Optimization Algorithm (COA) and a hybrid genetic- Nelder–Mead algorithm (GA-NM). Moradi et al. [15] utilized Bee Algorithm (BA) in order to identify depth and location of an open-edge crack created in a cantilever beam. Vakil-Baghmisheh et al. [18] found location and depth of a crack created in a cantilever beam using a hybrid method, combining Particle Swarm Optimization (PSO) and Nelder–Mead, which is denoted in abbreviated form as PSO-NM. They compared their innovative method to ordinary methods such as neural networks and GA-NM. They showed that results of their method in determining location and depth of a crack was far more accurate than ordinary methods. More studies can also be noted in which optimization methods are used for estimating and detecting cracks in engineering structures such as beams [19–22].

Regarding the foregoing points mentioned, some weaknesses of the above researches can be stated as follows:

- In most of researches mentioned, the proposed models for beam were valid only for simple and uniform Euler-Bernoulli beams and investigating dynamic models of more complex beams were ignored [4–6,8–12,15–22].
- In a number of these studies, the researchers had have just focused on finding and estimating the location and depth of a single crack in a beam and modeling the problems with multiple transverse cracks were ignored [1–6,14–22].
- In some of the researches, the process of solving the problem of crack estimation was so complex or didn't have enough accuracy due to the solution type which was analytical [5,7,10,14].
- Although optimization methods were used in a number of studies in order to improve the accuracy of estimating the location and depth of the cracks, the amount of calculations (number of function evaluations) were too many and the time consumed to solve the problem was not considered [15–22].
- In all models which used optimization methods to increase the accuracy, regardless of their relatively large amount of calculations, the solution was just confined to detect only a single crack in a simple and uniform beam [15–22].

In this study a procedure is used to estimate the location and depth of the created (single or multiple) crack(s) in simple (uniform) and complex (stepped) Euler-Bernoulli beams which leads to increase of accuracy and reduction of numerical calculations (i.e., function evaluations). In this process, a *new* and *hybrid* method called Cuckoo Optimization Algorithm-Nelder-Mead (COA-NM) is used for the solution. This method is a combination of two popular methods, the Nelder–Mead method and the COA.

One of the relatively new and powerful optimization methods that has been successfully used in a number of studies in recent years [23] is cuckoo optimization algorithm. COA is a population-based simple and effective method to solve many issues such as constrained optimization, dynamic optimization, and so on [17,24–26]. It includes a random population of solutions for the problem which is expressed as Cuckoo birds. By COA, the best points for a solution of the problem are searched, and then, by Nelder–Mead method the most accurate answer is searched in the search space.

The objectives mentioned and the algorithm performance are confirmed by using several predetermined numerical tests, such as detecting single or multiple cracks in simple and more complex beams like stepped beams, and also some experimental modal tests.

In order to model several cracks in a simple and more complex (stepped) Euler-Bernoulli beam, the TMM is used in this paper. Cracks created on the beam is modeled using a torsional spring, the stiffness of which is a function of crack depth.

In order to detect the locations and depths of the cracks in the Euler-Bernoulli cantilever beams, COA-NM is applied to minimize a cost function, which is based on the difference between measured and calculated frequencies. Results of the proposed method are compared with those of other popular methods such as GA [27], PSO [28], COA, and two hybrid optimization methods, GA-NM and PSO-NM and also a number of the past researches. Finally, some experimental modal tests are proposed in order to validate the simulation results.