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An improved CSS for damage detection of truss structures using changes in natural frequencies and mode shapes

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ABSTRACT

Non-destructive structural damage identification can be carried out using the difference between a structure's characteristics before and after a catastrophic event. An approach is to formulate the problem as an inverse optimization problem, in which the amounts of damage to each element are considered as the optimization variables. The objective is to set these variables such that the characteristics of the model correspond to the experimentally measured characteristics of the actual damaged structure. Since the structures are usually symmetric, this is an optimization problem with several global optimal solutions each representing a probable state of damage, where unlike many other optimization problems, it is not enough to merely find one of these optimal solutions; it is important to capture all such possible states and to compare them. In this paper, structural damage detection of planar and spatial trusses using the changes in structures' natural frequencies and mode shapes is addressed. An improved Charged System Search algorithm is developed and utilized to tackle the problem of finding as many global optimal solutions as possible in a single run. A 10-bar planar truss and a 72-bar spatial truss are considered as numerical examples. Experimental results show that it is important to incorporate mode shapes in order to determine the actual damage scenario among other possibilities.

1. Introduction

In a previous work, the authors introduced a simple method for detection and assessment of damage in trusses using the changes in structural natural frequencies as an optimization problem [1]. Structures can be damaged due to many different reasons in their lifespan. Finding the locations and the measurements of these damages, which is undeniably important to maintain the structural safety, is not always possible through visual inspection. Therefore, the responses of the structure and the changes occurred in them due to damage is viewed as a means to assess structural damage. Being accurately measurable and independent from the external excitation, natural frequencies of the structure are among the best response candidates for this purpose [2].

One of the most important aspects of evaluation of structural systems and ensuring their lifetime safety is structural damage detection [3]. Damages may be caused due to different reasons from manufacturing defects in structural materials to deterioration under service loads. These damages may endanger structure's integrity and functionality and need to be accurately detected.

Damage causes changes in structural parameters (e.g. the stiffness of a structural member), which in turn, alter the dynamic properties (such as natural frequencies and mode shapes) [4]. Among different structural responses that can be used as measures of structural damage, modal parameters enjoy the benefit of being independent form external excitation. Natural frequencies are more easily obtainable than mode shapes and less vulnerable to experimental errors. So, they have been used extensively in the formulation of inverse problems of damage detection. An inverse problem may be defined as determination of the internal structure of a physical system from the system's measured behavior or identification of the unknown input that gives rise to a measured output signal [5].

One of the earliest uses of natural frequencies for structural damage detection is due to Cawley and Adams [6]. Hassiotis and Jeong used and observation of the sensitivity of eigen frequencies to local stiffness reduction to detect the reduction in stiffness [7]. Nikolakopoulos et al. [8] used of contour graph forms to show the dependency of the first two structural eigen frequencies on crack depth and location. Ruotolo and Surace utilized a genetic algorithm to address the problem of non-destructive location and depth measurement of cracks in beams formulated as an inverse optimization [9]. Cerri and Vestroni investigated the problem of

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finding damaged zones in beam models using the reduction of the stiffness occurring in the damaged region. They used natural frequencies to measure this stiffness reduction [10]. Liu and Chen [11] explored the problem in frequency domain introducing a computational inverse technique for identifying stiffness distribution on structures using structural dynamics response. Maity and Tripathy [2] used a genetic algorithm for the detection of structural damage by the use of changes in natural frequencies. Sahoo and Maity [12] proposed a hybrid neuro-genetic algorithm and considered both natural frequencies and strains as input parameters to address the problem of damage detection. Mehrjoo et al. [3] used artificial neural networks for the damage detection of truss bridge joints using both natural frequencies and mode shapes.

Charged System Search (CSS) is a population based meta-heuristic optimization algorithm which has been proposed recently by Kaveh and Talatahari [13]. In the CSS each solution candidate is considered as a charged sphere called a Charged Particle (CP). The electrical load of a CP is determined considering its fitness. Each CP exerts an electrical force on all the others according to the Coulomb and Gauss laws from electrostatics. Then the new positions of all the CPs are calculated utilizing Newtonian mechanics, based on the acceleration produced by the electrical force, the previous velocity and the previous position of each CP. Many different structural optimization problems have been successfully solved by the CSS [13–16].

In this paper an improved Charged System Search is utilized for the damaged detection of truss structures using changes in natural frequencies. This is an inverse optimization problem with several probable global optimal solutions and the improvements on CSS are directed toward the proper handling on these global optima. Although the existence of these multiple global optimal solutions is viewed here as an opportunity to improve a meta-heuristic algorithm to find all global optimal solutions in a single run, it can also be viewed as a problem from damage detection point of view. Some of the mode shapes information of the damaged structures is used to address this problem.

The remainder of this paper is organized as follows: The formulation of the problem under consideration is briefly stated in Section 2. In Section 3, the optimization algorithm is presented. A brief background of the standard CSS is also represented. Numerical examples are studied in Section 4. Finally, the concluding remarks are provided in Section 5.

2. Problem formulation

In this section damage detection of structures using changes in natural frequencies is briefly described. Displacement based finite element equations are summarized first.

2.1. Finite element equations

A planar/spatial truss structure is modeled using two dimensional bar elements with two/three degrees of freedom at each end. From finite elements theory, the corresponding stiffness and mass matrices in element coordinate system can be expressed as [17]:

$$[\mathrm{k}] = \frac{EA}{L}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{1}$$

$$[\mathrm{m}] = \frac{\rho AL}{6}\begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \tag{2}$$

In which, A, E, L and ρ are cross-sectional area, modulus of elasticity, length and density of the member, respectively. These matrices can be transformed into global coordinates using following relations:

$$[\mathrm{K}] = [\mathrm{T}]^t[\mathrm{k}][\mathrm{T}] \tag{3}$$

$$[\mathrm{M}] = [\mathrm{T}]^t[\mathrm{m}][\mathrm{T}] \tag{4}$$

in which T is the transformation matrix. For planar truss the transformation matrix [T] can be written as:

$$[\mathrm{T}] = \begin{bmatrix} c & s & 0 & 0 \\ -s & c & 0 & 0 \\ 0 & 0 & c & s \\ 0 & 0 & -s & c \end{bmatrix} \tag{5}$$

where $c = \cos\alpha$ and $s = \sin\alpha$, α being the angle between the element and the global axis X. Similarly, for a spatial truss the transformation matrix [T] can be written as:

$$[\mathrm{T}] = \begin{bmatrix} \xi_1 & \xi_2 & \xi_3 & 0 & 0 & 0 \\ \eta_1 & \eta_2 & \eta_3 & 0 & 0 & 0 \\ \zeta_1 & \zeta_2 & \zeta_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & \xi_1 & \xi_2 & \xi_3 \\ 0 & 0 & 0 & \eta_1 & \eta_2 & \eta_3 \\ 0 & 0 & 0 & \zeta_1 & \zeta_2 & \zeta_3 \end{bmatrix} \tag{6}$$

where $\{\xi_1, \eta_1, \zeta_1\}$ are the direction cosines of the global axis X with respect to local xyz coordinate system. Similarly, $\{\xi_2, \eta_2, \zeta_2\}$ and $\{\xi_3, \eta_3, \zeta_3\}$ are direction cosines of global Y and Z axes with respect to xyz coordinate system respectively.

The dynamic equation which governs the behavior of an undamped structure is:

$$[\mathrm{M}]\{\ddot{x}\} + [\mathrm{K}]\{x\} = 0 \tag{7}$$

2.2. Damage formulation

Here, damage is considered as a reduction in stiffness which is incorporated into the equations by a reduction factor β. When damage occurs in an element, the stiffness matrix of the element is modified as:

$$[\mathrm{k}_{id}] = \beta_i[\mathrm{k}_i] \tag{8}$$

Here, the parameter β ranges from 0.7 to 1 introducing a maximum of 30% damage in each element i.e. it is assumed that the damage to the elements is previously known to be small. In practice, this could be verified by observing that the natural frequencies of the structure are not drastically changed after the damage imposing event.

The mass matrix [M] of the structure is assumed to be unchanged. The jth eigenvalue equation of the damaged structure will be derived by substitution of the structure's stiffness matrix by that of the damaged one:

$$[\mathrm{K}_d]\{\phi_{jd}\} - \omega_{jd}^2[\mathrm{M}]\{\phi_{jd}\} = \{0\} \tag{9}$$

in which, ω_{jd} and ϕ_{jd} are the jth natural frequency and the jth shape mode of the damaged structure, respectively.

2.3. Objective function

Two different objective functions are considered in this study. The first objective function which merely considers the natural frequency information of the structure is defined as:

$$F(X) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(f_i^a(X) - f_i^c(X)\right)^2} \tag{10}$$

where X is the solution vector representing the state of damage; n is the number of natural frequencies involved in the objective function; f_i^a and f_i^c are the ith actual (measured) and computed natural frequencies, respectively.