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Damage detection of plate-like structures based on residual force vector

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Abstract Structural health monitoring is essential to maintain the structural integrity by predicting problems in an early time. This consequently could be reflected on extending the life time of structures. Nondestructive tests based on dynamic measures are usually fast and economic in detecting damages of structures. Various numerical techniques together with recording time histories are used for this purpose. This paper presents a numerical method for damage detection in plate-like structures. The modeling of damage was conducted commercially using the module of MatLab. Comparison of different mode shapes was used in the analysis to detect the location of local damage based on residual force vector. The technique utilized the node residual force vector to locate and evaluate the degree of the suspected damaged elements. In the current study, three configurations for plates were used. The study also concentrated on the efficiency of the new method in identifying damages of different degradation levels. The plates were subjected to different combinations of artificial damages applied at various positions on each plate. The study was not only able to identify the location but also the degree of damage in plates. It has been noted that identification of severe degradation was more precisely identified. As a result, the residual force method is the simplest damage quantification technique which approved to be accurate enough to be used in practical applications.

Introduction

Accumulation of damage among structure can cause severe structural failure. Development of an early damage detection method for structural failure is one of the most important keys in maintaining the integrity and safety of structures. The dynamics-based damage detection is an effective method due to its simplicity of implementation and ability of acquiring both global and local information of structure. Significant efforts have already been spent to develop damage detection algorithms using dynamics-based approach [1].

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Techniques based on dynamic parameters for detecting damages in a structure have attracted much attention in recent years. Modal frequencies and mode shapes are the most popular parameters used in damage identification. The basic idea of these techniques is that modal parameters are functions of physical properties of structure (mass, damping and stiffness). Therefore, changes in physical properties will cause changes in modal properties. Many methods were developed recently using modal parameters as damage indicators.

An important class of damage identification methods is based on the updating or modification of structural matrices. The residual force vector is widely used in many damage detection methods using optimal matrix modification. Chen et al. [2] put forward a theory for assessing the occurrence, location and extent of potential damage using on-orbit response measurements. This method detects damages by using the minimum norm solution of the residual force equation. Zimmerman et al. [3] made use of a minimum rank update theory to detect structural damages. The damage sites are located firstly by the residual force vector and the damage extents are assessed by the minimum rank update theory. Doebling [4] improved this method and presented a new technique termed the minimum-rank elemental update by computing the minimum rank updates directly to the elemental stiffness parameters, Leandro et al. [5] and Damir et al. [6]. Chiang et al. [7] presented a two-stage structural damage detection method. The residual force vector is used to localize damages preliminarily and the simulated evolution method is employed to determine damage extents. Mares and Surace [8] proposed a genetic algorithm to identify damage in elastic structures. The location and quantification of the extent of the damage is performed with genetic techniques implemented by using the residual force method, which is based on conventional modal analysis theory. In short, these above methods all begin with the residual force vector but use different techniques to obtain damage extents, so the accuracy of the residual force vector is very important to those methods. The minimum norm method is shown to be unfeasible in damage identification in practice because the residual force equation is ill conditioned with the measurement noises, while the minimum rank update techniques can obtain better results only when the number of modes used in calculation equals the rank of perturbed matrix. Ratcliffe [9] develops and presents the Laplacian operator on the mode shapes to locate damage. When the damage is severe, the results are successful. For minor damages a further processing of the Laplacian output is required. The procedure operates solely on the mode shape from the damaged structure, and does not require a priori knowledge of the undamaged structure.

Pandey et al. [10] employed the change in the mode shapes curvature to detect damage. The curvatures are obtained using a central difference approximation. Hajela and Soeiro [11] studied structural damage detection based on static and modal analysis. Chakraverty et al. [12] and Leandro et al. [13] have been studied the effect of non-homogeneity and different parameters on natural frequencies of vibration for plate damage detection. In a situation with little displacements, the curvature approximation becomes very sensitive to the presence of noise. Identifying the structural damage with the measured vibration data is an inverse approach in mathematics. The usual damage detection methods minimize an objective function, which is defined in terms of the discrepancies between the vibration data identified by modal testing and those computed from the analytical model. Titurus et al. [14] discussed damage detection using successive parameter subset selections and multiple modal residuals.

The purpose of this work is to use the residual force method in order to detect structural damages successfully in plate structures. Also, to verify the efficiency of the developed technique on different structures with different damage ratios. Computer program using MatLab is employed to find out the location and extent of the damage.

Theory and modeling

Numerical simulation

The equation of motion of the structure when subjected to dynamic loads is:

$$M\ddot{y} + C\dot{y} + Ky = F \tag{1}$$

where M, C, and K are the mass, damping and stiffness matrices of the structure, respectively. $\ddot{y}, \dot{y},$ and y are the acceleration, velocity and displacement vectors of the structure, respectively. F is the dynamic force. The mass and stiffness matrices of the structure are computed by the assembly of mass and stiffness matrices of the structure elements. In this section, the global stiffness and mass matrices in case of plate elements will be derived.

The plane stress equations can be used to relate the in-plane stresses to the in-plane strains for an isotropic material as:

$$\sigma_x = \frac{E}{1-\upsilon^2}(\varepsilon_x + \upsilon \cdot \varepsilon_y) \tag{2}$$

$$\sigma_y = \frac{E}{1-\upsilon^2}(\varepsilon_y + \upsilon \cdot \varepsilon_x) \tag{3}$$

$$\tau_{xy} = G\gamma_{xy} \tag{4}$$

where σ_x and σ_y are the normal stress in X and Y directions, respectively. τ_{xy} is the shear stress acts on the X edge (vertical face) in the Y-direction.

Fig. 1 shows the plate structure model and the schematic diagram of four nodes plate. Each node has three degrees of freedom – transverse displacement ω in the Z-direction, rotation θ_x about the X-axis, and rotation θ_y about the Y-axis.

The nodal displacements at node i can be presented by [15]:

$$\{d\} = \begin{Bmatrix} w_i \\ \theta_{xi} \\ \theta_{yi} \end{Bmatrix} \tag{5}$$

where the rotations are correlated to the transversal displacements by:

$$\theta_x = +\frac{\partial w}{\partial y}, \quad \theta_y = -\frac{\partial w}{\partial x} \tag{6}$$

The negative sign of θ_y is due to the fact that a negative displacement ω is required to produce a positive rotation about the Y-axis.

The total element displacement matrix is now given by:

$$\{d\} = \{d_i \quad d_j \quad d_m \quad d_n\}^T \tag{7a}$$

The constants a_1 through a_{12} can be determined by expressing the 12 simultaneous equations linking the values of ω and its slopes at the nodes when the coordinates take up their appropriate values.

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