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A damage identification strategy in beams based on natural frequencies shift

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Abstract

This paper presents a damage identification technique based on the frequency changes between healthy and damaged beam structure. An algorithm based on frequency shift coefficient (FSC) is proposed, and the sensitivity of eigenfrequencies is studied. The method is tested by introducing an artificial damage, which depends on local stiffness reduction using five frequencies. The modal analysis technique is employed for healthy and damaged 2D Euler-Bernoulli beam modeled with Finite Element by using mass and stiffness matrices in order to provide natural frequencies. The effect of uncertainty on natural frequencies (0.1%, 0.2% and 0.3%) in damaged case is considered, and samples are used to estimate the average damage position and severity. In the beginning, the damage is localized and quantified. Then, the sensitivity of eigenfrequencies is investigated based on added uncertainty. The conclusion of analyses indicates that the algorithm correctly localizes and accurately estimates the damage by requiring a short amount of computational time.

1 Introduction

Structural integrity evaluation based on vibration analysis is an important aspect for researchers and scientific committee. There are many critical mechanisms in a structure that can cause for damage. However, the presence of damage can causes changes in the physical parameters (mass, stiffness and damping) and geometry parameters (thickness, length, height, etc.). Therefore, changes in the natural frequencies and mode shapes of the structure. One of the most suitable techniques to identify the presence of damage and assess the structure is vibration-based structure health monitoring (VBSHM). Doebling *et al.* [1], Montalvao [2] and Sohn *et al.* [3] presented reviews covering on VBSHM based on advances in damage detection and SHM with an emphasis on structures. Rytter [4] defined four levels for damage detection and assessment: (i) detection (ii) localization (iii) quantification (iv) prediction of the remaining life of the structure. The first step for structural identification is to compare the natural frequencies of healthy beam and unknown beam. If the frequency shift remains, then there is a chance that damage is present in the structure. The frequencies are commonly used modal parameters for identification of defect as they are sensitive for different types of damage. Cawley and Adams [5] introduced sensitivity analysis using natural frequencies to detect, locate and quantify damage. Salawu [6] mentioned that natural frequency is a sensitive parameter and measurements of frequencies can be quickly conducted and are reliable. Messina *et al.* [7] presented damage location assurance criterion (DLAC) and after multiple damage location assurance criterion (MDLAC) based on natural frequency changes. Silva and Gomes [8] introduced frequency shift coefficient to detect damage position and estimate crack length. Shukla and Harsha [9] acknowledged that the changes in natural frequency are an indication of cracks in the blade geometry. Zhang *et al.* [10] presented techniques based on vibration methodologies by the frequency shifts from three inverse algorithms based on graphical technique, surrogate-assisted optimization and artificial neural network, to predict the location, size and interface of damages in the composite beam. Le *et al.* [11] employed a method based on the first-order analytical estimation value of the relative variations of eigenfrequencies due to the change in mass and/or rigidity from the estimation of the modal parameters. Serra *et al.* [12] examined numerical damage case using different

indicators and a damage library was created from 3-D and 2-D Finite Element (FE) model of a cantilever beam from considering bending frequencies. Serra and Lopez [13] compared many classical indicators to evaluate their performance and capacity to detect and localize damage from different cases.

In this paper, a FE based algorithm using modal analysis technique is proposed for a cantilever beam structure. The vibratory response of the structure is tested with two states: the healthy state and the damaged state. Localization and quantification of damage are calculated from these two states using frequency variations. The main objective of this paper is to implement the proposed algorithm which can be used for damage identification based on the frequency shift between healthy and damaged structure. In order to validate the proposed damage identification algorithm, at first, the algorithm is implemented between FE models to identify damage. Then noise levels or uncertainty levels on natural frequencies (0.1%, 0.2% and 0.3%) are tested by adding random noise in damaged beam frequencies. In each noise level, ten samples are used in damaged beam frequencies to estimate the average damage position and severity. Finally, the sensitivity of the algorithm is mentioned through the identification of damage case with or without noise levels.

The paper is organized as follows. In Section 2, a brief introduction about beam bending vibration theory for 2D FE model is presented to extract the modal parameters from a structure. In Section 3, the steps of proposed strategy and variation in frequencies using random noise function are illustrated. In Section 4, a numerical case is tested, and results are analyzed employing noise levels in damaged beam frequencies. In Section 5, the conclusion is drawn based on the proposed algorithm using the different noise levels.

2 Beam vibration model

The study model focuses on a Euler's-Bernoulli cantilever beam structure, as shown in Fig. 1. The beam is modeled with 100 elements, and each element size is 10 mm. The 2D FE model has a the total number of 202 degree of freedoms (DOFs), where each node has 2 DOFs: displacement along y-axis and rotation (θ_z) along the z-axis.

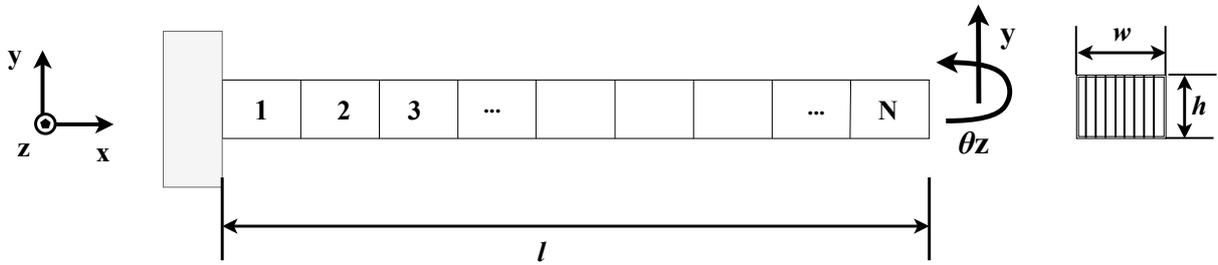


Figure 1: 2D FE model of a cantilever beam and cross-section area.

The formulation of the equation of motion for each degree of freedom can be described in matrix form:

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{F\} \quad (1)$$

where $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices, respectively. Here, X stands for a nodal displacements vector. Considering no external force and damping, the eigenvalue equation for the i th vibration mode of a dynamic structure is expressed as:

$$([K] - \lambda_i[M])\phi_i = 0 \quad (2)$$

where λ_i and ϕ_i are the i th eigenvalue and eigenvector, and where $\lambda_i = \omega_i^2$ in which ω_i is the i th natural frequency. In this particular 2D FE approach, it is assumed that the damage only affects the stiffness of selected elements. In this study, an artificial damage is simulated by reducing the bending stiffness of the selected element. Damage severity is represented by the stiffness reduction coefficient β_e , which is the ratio of stiffness reduction to the initial stiffness.

The following equation defines the stiffness matrix of a damaged beam:

$$[K_d] = \sum_{e=1}^n (1 - \beta_e) [K_e] \quad (3)$$

where $[K_d]$ is global stiffness matrix for a damaged beam, $[K_e]$ is the element stiffness matrix for element e , n is the number of elements, and β_e is a bending stiffness reduction parameter, which varies from 0 to 1 for the damaged structure. The value of $\beta_e = 0$ indicates a healthy element.

3 Proposed damage identification strategy

This work presents a strategy based on natural frequencies for locating and estimating damage in a beam discretized using FE. The strategy focuses on the shift of natural frequencies between healthy and damaged beam, whereas 2D FE models are simulated in order to perform damage identification. To achieve this goal, the damage is identified by updating a FE model using a criterion based on natural frequencies. The identification is performed by the use of four sets of natural frequencies : on the one hand, a healthy beam and a damaged one, the latter being to identify, on the other hand, a 2D healthy beam model and damaged one, the latter being updated. Here, the strategy uses numerical computation of frequencies along with the damage position and 1 to 99% stiffness reduction, as the study is carried out using the FE model updating. To sum up, the strategy consists in updating the stiffness of an FE model, based on frequency shifts. The numerical solution of damage case is obtained with the use of FE model updating approach. Finally, the strategy is carried out in order to investigate the sensitivity of the eigenfrequencies.

3.1 Objective function and minimization procedure

In this study, a Frequency Shift Criterion (FSC) is employed during minimization procedure to find the position and severity percentage. This FSC is first presented by Silva and Gomes [8] for damage identification problems. The FSC is expressed as:

$$\text{FSC} = \sqrt{\frac{1}{m} \left\| \sum_{i=1}^m \left(\frac{(R_i)_D - (R_i)_A}{(R_i)_X} \right) \right\|^2} \quad \text{and} \quad R_i = \frac{\omega_i^d}{\omega_i^h} \quad (4)$$

where R_i is the ratio of damaged (ω_i^d) and healthy (ω_i^h) beam frequencies, m is the total number of frequencies, D refers to the damaged case, A refers to the reference i.e. safe FE model to be updated, and i denotes frequencies indices. At least two vibration frequencies must be considered for the evaluation of the FSC.

In the minimization procedure, the updating parameters are set by the vectors of positions $[p_1, p_2, \dots, p_N]$ and severities $[\beta_1, \beta_2, \dots, \beta_N]$. The objective of 2D FE updating is to obtain the best-fit value through the minimization procedure between 2D FE model to be updated and tested damaged case. The parameters minimizing FSC correspond to the position and severity of the damaged case.

Practically, the minimization problem is solved using Particle Swarm Optimization (PSO) [14]. Several other techniques may be employed, but the main reasons behind this choice is that a global solution must be found and the gradient of the cost function i.e. the FSC, is difficult to define or to estimate. In practice, the PSO (as implemented in the `particleswarm()` function in MATLAB Global Optimization Toolbox) proves to be adequate to solve the problem.

There are many parameters in PSO, i.e., swarm size, number of iterations, inertia weight, learning factors, etc. The influence of PSO parameters are not considered during minimizing procedure. Only the swarm size and the number of maximum iterations are explicitly specified during FSC minimization, with values of 10 and 50, respectively.

3.2 Algorithm

The main steps for the proposed algorithm are summarized as follows:

Step-1: Generate damage case with the bending stiffness reduction ranging between 0.01 and 0.99 with a step of 0.01.

Step-2: Develop the FE models of the beam structure in order to compute natural frequencies as for healthy and given damaged case from step-1. Optionally, add a perturbation to the set of frequencies of the damaged case in order to simulate measurement imprecision.

Step-3 : Using the FSC and the minimization algorithm, update a beam FE model with a generic defect, for each set of tested frequencies.

Step-4 : Consider the updated parameters as the damage parameters. In the case where perturbations are introduced, consider the mean and standard deviation of the results.

3.3 Modeling uncertainty on natural frequencies

Measurement imprecision always exists in the experimentally measured frequencies as well as other modal parameters. In this study, artificial uncertain cases, i.e. cases whose natural frequencies are incorrectly estimated, are generated numerically, and the effect on the results are analysed based on the proposed algorithm. The uncertain or noisy cases are introduced in damaged beam frequencies by the addition of percentage noise levels with assumed normally distributed random variables. In this regard, the uncertain or noisy damaged beam frequencies can be expressed as:

$$\bar{\omega}_i^d = \omega_i^d(1 + \eta\gamma_i) \quad \text{and} \quad i = 1, 2, \dots, n_m \quad (5)$$

where $\bar{\omega}_i^d$ is i th damaged beam frequency after noise addition, η is the percentage of noise, and γ_i is a Gaussian random number between -1 to 1, different for each i .

4 Results and discussions

To investigate the proposed strategy and evaluate the performance of the algorithm, we propose to identify a damage location and severity on a Euler-Bernoulli cantilever beam. Furthermore, on a given damaged case, we will estimate the sensitivity of the algorithm by introducing a perturbation on the natural frequencies as presented in Eq. 5.

The steel beam properties and dimensions are listed in Table 1. The artificial damage is introduced by reducing the stiffness of the individual element. Here, the damage case is set at 0.8 m beam position by 50% stiffness reduction. The first five lowest natural frequencies of the healthy and damaged beam are extracted from the respective FE models. The result may vary with consideration of more than five frequencies. However, it is also essential to reduce the computation time. Hence, five frequencies prove to be sufficient to identify the considered structural modifications. The frequencies of healthy and damaged beam are reported in Table 2. Three significant digits are kept in the natural frequencies, which is enough for the algorithm to work accurately and identify a damage.

In a first step, the damage of the tested case is identified based on the exact natural frequencies. The Frequency Shift Criterion is minimized in order to identify position and severity of the damage. In Fig. 2, the FSC is plotted in color levels as a function of position and severity. The red circle denotes real damage position and severity (%) while the cross symbol is obtained from minimizing the FSC using PSO; The locus of the FSC lowest value corresponds to the result of the minimization and also to the exact parameters. Essentially, it shows that the criterion is valid and that the minimization yielded the expected result. Note that the computational time for minimization using PSO is approximately 10 s.

Table 1: Steel beam properties and dimensions.

Properties	Value
Length (l)	1 m
Width (w)	0.0249 m
Height (h)	0.0054 m
Poisson's ratio (ν)	0.33
Mass density (ρ)	7850 kg/m ³
Young's modulus (E)	210 GPa

Table 2: Numerically identified natural frequencies of healthy and damaged beam.

Beam case	Natural frequencies (Hz)				
	1	2	3	4	5
Healthy	4.554	28.537	79.904	156.579	258.837
Damaged (0.8 m with 50%)	4.553	28.480	79.294	154.845	256.882

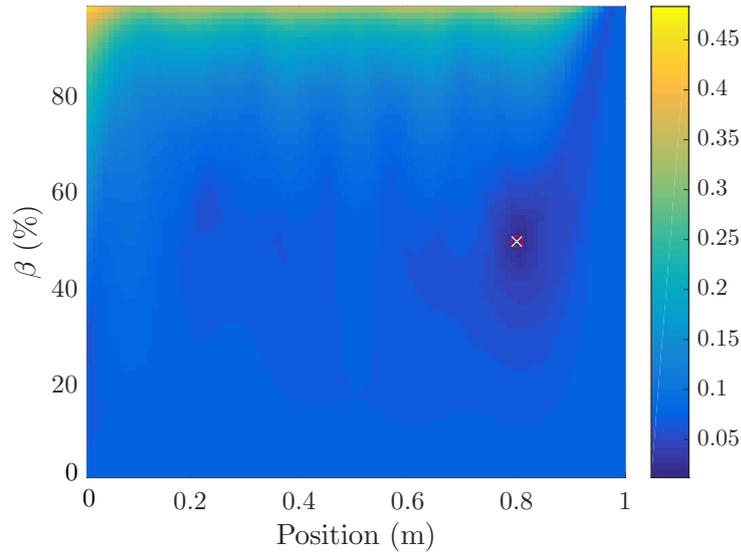


Figure 2: FSC as a function of position and damage (%). The red circle denotes a real damage case, where cross symbol and colorbar indicate the lowest minimized value corresponding to identified 0.8 m beam position with 50% damage severity.

In a second step, the natural frequencies of the tested case are perturbed by adding noise with $\eta = 0.1, 0.2$ and 0.3% . It is important to notice that the algorithm does not affect by the addition of the noise levels. By these noise levels, the algorithm works accurately for the localization and estimation of the damage. Using Eq. 5, 10 random samples are generated by `randn` MATLAB function based on the tested damaged case. Each sample i.e. each set of five natural frequencies is used in the minimization procedure in order to estimate damage parameters.

The results are represented in Fig. 3, where the red dot represent real damage position and severity i.e. without perturbation. Green, blue and black stars denote identified damage parameters for 0.1%, 0.2% and 0.3%, perturbation levels, respectively. Average values of positions and severities are 0.806 m, 0.808 m, 0.811 m and 50.37%, 50.07%, 51.54%, respectively. The standard deviation values for obtained positions and severities are 0.006 m, 0.022 m, 0.024 m and 1.56%, 3.65%, 5.09%, respectively.

The average identified damage parameters for 0.1%, 0.2%, and 0.3% perturbation levels are really close to

real identified damage parameters. These results are a good way to represent the sensitivity of the criterion and algorithm. Sensitivity is not negligible and show that a precise estimation of natural frequencies is needed.

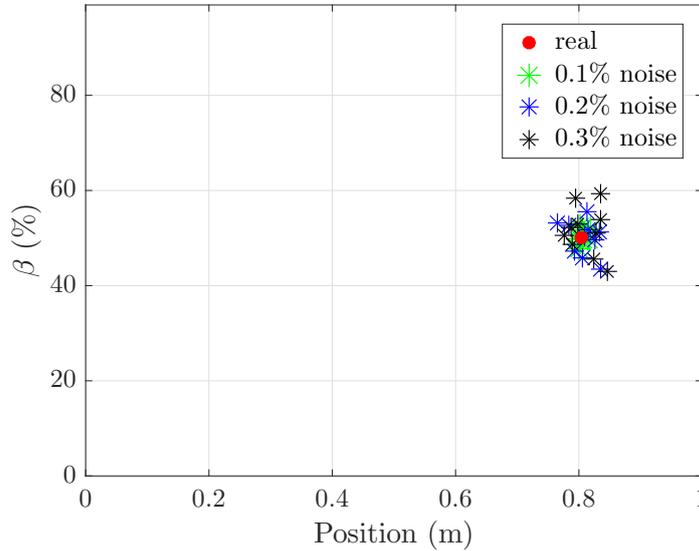


Figure 3: Real and identified damage positions and damage (%) concerning for ten samples with 0.1%, 0.2% and 0.3% random noise levels.

5 Conclusion

The present work focused on damage localization and quantification with an algorithm using FE models and the minimization of a Frequency Shift Criterion. As small errors are inevitable in the estimation of experimental frequencies, the sensitivity of the criterion to the natural frequencies of the beam is investigated by considering the perturbation of these frequencies at different levels. Each random perturbation provides a different set of damage parameters. On average, these parameters depends on the perturbation level but are close to the real ones; sensitivity is given by the standard deviation on a number of sample. Sensitivity is not negligible. The numerical results demonstrated that damage positions and severities may be correctly identified by minimizing the FSC with or without perturbation, within a small computational time. The results are validated for several cases (different damage levels and position, several perturbation levels). Future investigation on the identification of multiple damages, and damages on other structure needs to be conducted.

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