Mechanical Systems and Signal Processing 115 (2019) 361–379

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

A robust damage detection method based on multi-modal analysis in variable temperature conditions

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A R T I C L E I N F O

Article history:
Received 28 September 2017
Received in revised form 22 March 2018
Accepted 18 May 2018

Keywords:
Damage detection
Frequency shift
Temperature changes
Axial loads
Boundary conditions

A B S T R A C T

This paper proposes a method, based on multi-modal analysis, which permits assessing damages in beams subjected to axial forces induced by temperature changes. The effect of temperature is eliminated by employing adjustment coefficients, individually developed for each mode of vibration. If the beam is supported by elastic supports, these coefficients consider also the relative displacement at the beam ends. These coefficients can be used for the intact beam, as well as, for the beam with transverse cracks. Predictive models describing the vibration behavior of beam-like structures in healthy and damaged states are developed based. Numerical simulations and experimental tests were completed on beams with fixed ends to check the practical applicability of the proposed method in variable temperature conditions. The results validate the developed method that employs adjusting coefficients, which can be used for perfectly clamped beams, even if restraints allow a small longitudinal displacement.

1. Introduction

Vibration-based damage detection methods have gained an important place among current non-destructive evaluation testing procedures. These methods are based on observation and interpretation of the changes in modal parameters. An ample survey on vibration-based structural health monitoring and damage detection techniques for civil and mechanical engineering structures was given in [1]. Methods implying the changes in frequencies to detect structural damage were largely discussed in [2]. A review of inverse methods that use measured vibration data for damage detection was presented in [3]. Structural health monitoring methods with emphasis on composite structures have been described in [4], while single or multiple crack detection in piezoelectric structures was the subject of [5–7].

In real cases, monitoring of structures requires consideration of operational and environmental effects. Temperature changes sometimes generate bigger changes in parameter than the effect of damage in early state, thus it becomes difficult to distinguish between the two causes. Various approaches to extract the effects of temperature from the modal parameters were presented in the literature [8–10]. Predictive models, considering the effects of temperature on the modal parameters, can be obtained if measurements in different temperature conditions are available. A conventional structural model is obtained for each temperature, afterwards interpolation procedures are used to approximate the dependence of the model

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https://doi.org/10.1016/j.ymssp.2018.05.037
0888-3270/

parameters on temperature [11,12]. In order to illustrate the thermal influence on the dynamics of the structure, linear models describing the frequency dependence on temperature have also been developed [13,14].

In spite of numerous studies, a debate regarding how temperature affects the natural frequencies still exists among researchers [15]. The modulus of elasticity alteration in a temperature condition different from the natural environment is insignificant [16], but can be taken into account in the analytical calculation of frequencies. On the contrary, axial forces arising in the beam due to temperature variation, changes the beam's dynamical behavior, leading to significant modifications in natural frequencies. The same process can also occur, to a lower extent, if a limited displacement at the ends of the beam is allowed. Importantly, if the beam is integrated into a complex structure, internal forces at the ends of the beam are to be expected. Therefore, for an element, which is a part of a complex structure, the temperature can produce internal and external forces. A simple measure for a global quantification of the effect of temperature is the deformation of the beam [17], which considers external and internal forces at once. Longitudinal deformation and vibration parameters can easily be measured and corroborated to get information about the system's state.

In this paper, we propose mathematical expressions to predict the changes in frequencies for an intact beam at any temperature, if the frequencies in the healthy state of the beam at a reference temperature, are known. Versions of these expressions can be used for damaged beams, if the damage parameters are known. The expressions are integrated into an algorithm; priory developed for damage assessment in beams for constant temperature [18,19], and is tested here in case of variable environmental conditions.

2. Description of the damage detection method

The damage detection approach followed here is based on the fact that each damage has a unique signature [20]. Expressed in terms of frequencies, this signature is best represented by the Relative Frequency Shift (RFS) of several weak-axis bending vibration modes. It was shown that, for a slender beam with length L, width b and thickness h, containing a crack with a depth a located at a distance x_D from the left end, which is taken as the origin of the coordinate system, as shown in Fig. 1, the frequency can be predicted using the following mathematical expression [21]:

$$f_{iD}(x_D, a) = f_i\left\{1 - \gamma(a)\left[\bar{\phi}_i''(x_D)\right]^2\right\} \tag{1}$$

where f_{iD} is the frequency of the damaged beam and f_i is the frequency of the healthy beam for the ith bending mode of vibration, and $\bar{\phi}_i''(x_D)$ is the normalized mode shape curvature vector of the healthy beam, found at the damage location.

The term $\gamma(a)$, which indicates the damage severity, is derived from the energy loss expressed using the beam deflections δ_U and δ_D achieved under dead mass in the healthy and damaged states, respectively [22]. Therefore, the severity is given by:

$$\gamma(a) = \frac{\sqrt{\delta_D} - \sqrt{\delta_U}}{\sqrt{\delta_D}} \tag{2}$$

Employing Eq. (1), RSF is obtained as:

$$\Delta\bar{f}_i(x_D, a) = \frac{f_i - f_{iD}(x_D, a)}{f_i} = \gamma(a)\left[\bar{\phi}_i''(x_D)\right]^2 \tag{3}$$

Fig. 2 shows the squared mode shape curvature and RSF's derived by means of the Finite Element Method (FEM) for the first bending mode of vibration of a beam with fixed-fixed boundaries. One can easily observe that the curves representing the frequency shifts follow the squared mode shape curvatures, which means that the curvature is in direct relation with the position. For the same damage position, the RFS amplitudes depend on the severity. The RFS curves in Fig. 2 are plotted for severities 0.0917 and 0.0673, respectively.

The effect of a given damage upon the natural frequencies can be described by a sequence of 'n' number of RFS's, i.e.:

$$\mathbf{F}: \left\{\Delta\bar{f}_1(x_D, a) = \gamma(a)\left[\bar{\phi}_i''(x_D)\right]^2, \ldots, \Delta\bar{f}_i(x_D, a) = \gamma(a)\left[\bar{\phi}_i''(x_D)\right]^2, \ldots, \Delta\bar{f}_n(x_D, a) = \gamma(a)\left[\bar{\phi}_i''(x_D)\right]^2\right\} \tag{4}$$

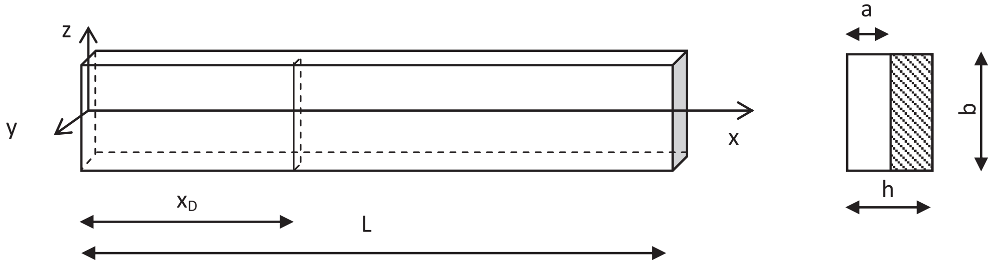

Fig. 1. Geometry of the cracked beam.