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Experimental study of sensitivity-aided application of artificial boundary condition frequencies for damage identification

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ABSTRACT

This paper presents an experimental study on the application of the so-called artificial boundary condition (ABC) frequencies for structural damage identification. Aided by the corresponding sensitivity analysis, more suitable ABC frequencies can be selected for improved identification of structural damage. An overview of the theoretical background of ABC frequencies and their sensitivity formulation is provided first. An experimental programme involving model steel beams in the intact and damaged states for the measurements of ABC frequency is presented, and the extraction of the ABC frequencies is descried and discussed. The extracted ABC frequencies are selected in accordance with the sensitivity analysis and they are subsequently employed to identify the structural damage. Results demonstrate that, aided by the sensitivity-based selection procedure, the ABC frequencies can be used for practical identification of structural damage and both the damage location and severity can be determined with good accuracy.

1. Introduction

In recent years, a lot of studies have been devoted to structural health monitoring and damage identification with model-based methods, particularly the finite element (FE) model updating techniques [1–10]. Many FE model updating techniques have been demonstrated to exhibit satisfactory identification performance in the numerical studies. However, in physical structures, measurement and environmental noises often dictate that only a limited amount of modal data, including natural frequencies, mode shapes and damping ratios, may be available with acceptable accuracy [11,14], and this restricts the extent to which damage may be identified from a model updating procedure.

Several studies have been conducted on structural damage identification using experimentally determined natural frequencies [2–4], and it has been found that damages in relatively simple structures, such as 1-dimensional beams, may be identified using the first few natural frequencies. In some latest studies (e.g. [10]), the natural frequencies of higher order modes have been used to identify the local damages in beam-like structures, and the results demonstrate that even small damages could be identified when higher order natural frequencies became available. However, for complex damage identification problems with a large number of variable parameters, using natural frequencies alone would not be sufficient, as the number of natural frequencies is still limited.

Similarly, mode shapes may be measured with good accuracy for relatively simple cases [12,9,13]; but even for simple structures problems can arise in measuring high modes if the structure is relatively stiff, or when significant nonlinearities are involved. Moreover, pronounced structural damage may cause variation of mode order and this can complicate an accurate determination of higher-order mode shapes. Therefore, it would be desirable if additional modal information can be generated within the lower-order mode region for the general damage detection and structural identification.

In the above respect, alternative methods have been proposed to enhance the dataset of modal information for structural damage identification [15–18], including the incorporation of ABC frequencies which are essentially the perturbed natural frequencies of a structure with additional virtual supports. Several studies have been performed using ABC frequencies, as well as antiresonance frequencies, to identify structural damages, and results demonstrate that effective damage identification can be achieved with the use of such frequencies [19–24].

Despite the above advancements, the performance of using ABC frequencies from real measurements for damage identification has not been systematically studied. Moreover, since a large variety of perturbed boundary conditions, i.e. the ABC pin supports, may be

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configured for the ABC frequencies, the inherent information with the ABC frequencies requires further investigation so that more suitable ABC frequencies can be selected to ensure better identification performance. However, only limited research in the literature has been devoted to the selection of ABC frequency for damage identification [22,25].

In this paper, an experimental investigation into the extraction and application of the ABC frequencies for structural damage identification, aided by the sensitivity analysis of the ABC frequencies, is presented. An overview of the background theory about ABC frequency and the theoretical formulation of the ABC frequency sensitivity is provided first. The experiment was performed on model steel beams in the intact and damaged states, and dynamic measurements were taken for the processing and extraction of the ABC frequencies. Extracted ABC frequencies are presented and discussed. Subsequently, the extracted ABC frequencies are selected in accordance with the sensitivity analysis for the incorporation in the FE model updating procedure to identify the structural damage. Results demonstrate that it is possible to extract ABC frequencies from the experimental, and aided with a sensitivity based selection procedure, the ABC frequencies can be used for the identification of structural damage effectively and both the damage location and severity can be determined with good accuracy.

2. Theoretical background of ABC frequency

Modal frequencies of a given structure with perturbed support conditions provide extra modal information which may be incorporated to enhance the response dataset for structural damage identification. The practicality of such an idea is hindered by the fact that imposing added supports physically on a structure is not normally feasible. Gordis [16,19] introduced a theoretical approach by which a structure under a supposed set of additional pin supports can be derived from an incomplete frequency response function matrix measured from the original structure, without the need of actually imposing the additional pin supports, and hence the term of artificial boundary condition or ABC frequencies. Expressing the steady state response of a linear system at a forcing frequency ω (rad/s) in the following form:

$$\left(\begin{bmatrix}\mathbf{k}_{mm} & \mathbf{k}_{mo}\\ \mathbf{k}_{om} & \mathbf{k}_{oo}\end{bmatrix} - \omega^2\begin{bmatrix}\mathbf{m}_{mm} & \mathbf{m}_{mo}\\ \mathbf{m}_{om} & \mathbf{m}_{oo}\end{bmatrix}\right)\begin{Bmatrix}\mathbf{x}_m\\ \mathbf{x}_o\end{Bmatrix} = \begin{Bmatrix}\mathbf{f}_m\\ \mathbf{f}_o\end{Bmatrix} \tag{1}$$

where $\mathbf{k}$ and $\mathbf{m}$ are stiffness and mass matrices, $\mathbf{x}$ and $\mathbf{f}$ are vectors of generalized response and excitation amplitudes, respectively. Subscript 'm' represents measured coordinates or DOFs and subscript 'o' refers to the unmeasured DOFs ('omitted coordinate set' or OCS). The OCS is effectively a reduced system, where all the measured DOFs are restrained or pinned to the ground.

Introducing the impedance matrix, $\mathbf{Z} = \mathbf{k} - \omega^2\mathbf{m}$, Eq. (1) can be re-written as:

$$\begin{bmatrix}\mathbf{Z}_{mm} & \mathbf{Z}_{mo}\\ \mathbf{Z}_{om} & \mathbf{Z}_{oo}\end{bmatrix}\begin{Bmatrix}\mathbf{x}_m\\ \mathbf{x}_o\end{Bmatrix} = \begin{Bmatrix}\mathbf{f}_m\\ \mathbf{f}_o\end{Bmatrix} \tag{2}$$

Assuming there exist no excitation on the omitted coordinates, i.e., $f_o = 0$, Eq. (2) can be rearranged as:

$$\mathbf{f}_m = (\mathbf{Z}_{mm} - \mathbf{Z}_{mo}\mathbf{Z}_{oo}^{-1}\mathbf{Z}_{om})(\mathbf{x}_m) \tag{3}$$

Thus:

$$\mathbf{H}_{mm}^{-1} = \left(\mathbf{Z}_{mm} - \mathbf{Z}_{mo}\mathbf{Z}_{oo}^{-1}\mathbf{Z}_{om}\right) \tag{4}$$

where $\boldsymbol{f}_m$ is the generalized excitation at the measured coordinates or DOFs, $\boldsymbol{x}_m$ is the generalized response at these DOFs, and $\mathbf{H}_{mm}$ is the frequency response function (FRF) matrix measured from the structure.

From Eq. (4), it can be seen that at the natural frequencies of the OCS, $\mathbf{Z}_{oo}^{-1}$ is singular, so $\mathbf{H}_{mm}^{-1}$ is also singular. This means that by

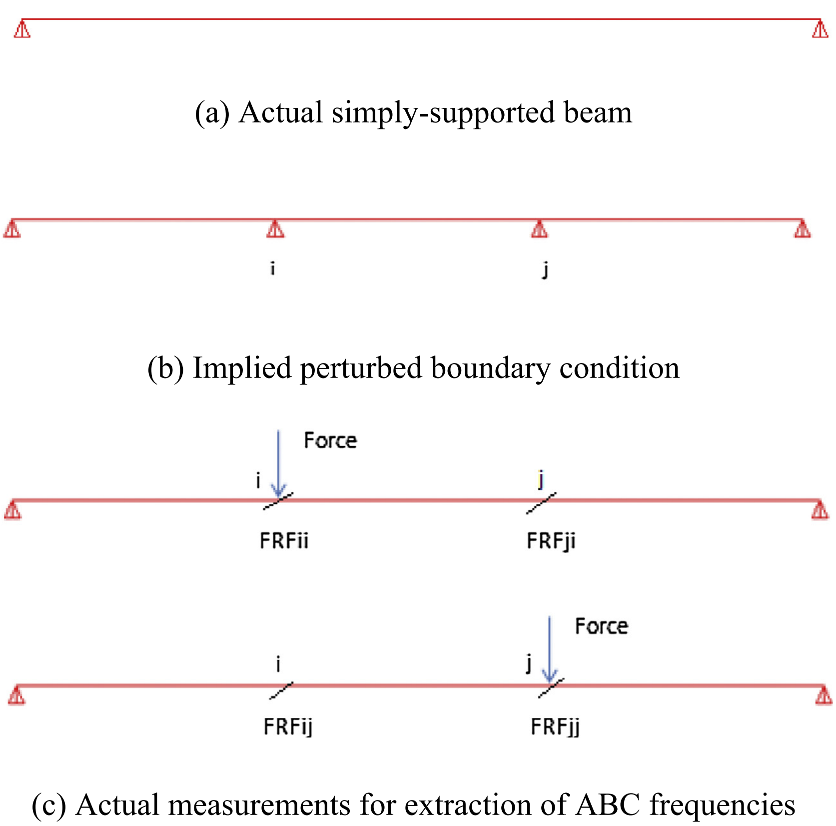

Fig. 1. Illustration of artificial boundary condition frequency measurement settings.