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A new scenario-based approach to damage detection using operational modal parameter estimates

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ABSTRACT

In this paper a vibration-based damage localization and quantification method, based on natural frequencies and mode shapes, is presented. The proposed technique is inspired by a damage assessment methodology based solely on the sensitivity of mass-normalized experimental determined mode shapes. The present method differs by being based on modal data extracted by means of Operational Modal Analysis (OMA) combined with a reasonable Finite Element (FE) representation of the test structure and implemented in a scenario-based framework. Besides a review of the basic methodology this paper addresses fundamental theoretical as well as practical considerations which are crucial to the applicability of a given vibration-based damage assessment configuration. Lastly, the technique is demonstrated on an experimental test case using automated OMA. Both the numerical study as well as the experimental test case presented in this paper are restricted to perturbations concerning mass change.

1. Introduction

In the academic as well as the industrial world the interest in the ability to monitor and detect damage(s) in a civil or mechanical structure is immense. For decades researchers and practitioners in the Structural Health Monitoring (SHM) community have been developing an extensive amount of methods based on a wide range of physically interpretable structural features. At this point in time there is no universal monitoring system hence the term SHM refers to the implementation of one or more damage identification strategies [1].

In vibration-based damage detection the underlying premise is that the modal parameters are governed by the physical properties of the structure, hence an observed shift in the modal parameters indicate changes in the inherent properties of the monitored structure (e.g. structural degradation). Even though the area of vibration-based damage evaluation is merely a branch of SHM, the literature produced in this area alone is extensive [2,3]. The capabilities of a given damage technique has through many years been classified in reference to Rytters four levels of damage identification [4]. The four levels are as follows:

1. Detection - Is the structure damaged?
2. Localization - Where is the damage?
3. Quantification - How severe is the damage?
4. Prognosis - What is the remaining service life of the structure?

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The vibration-based methods range from simple tracking of natural frequencies, fundamental relations between the modal parameters and the system matrices, to modal-based Finite Element (FE) model updating. Methods utilizing only the natural frequencies usually fall into to the level 1 category whereas level 2–3 techniques also require the corresponding mode shapes. Since, the modal parameters, traditionally, have been extracted by means of Experimental Modal Analysis (EMA) many techniques capable of localizing damage, without depending on a parametric model, require scaled or mass normalized mode shapes. This fact rules out the immediate application of most vibration-based localization methods to structures which cannot be subjected to a controlled vibration test (i.e. where the input force is known).

Over the last decades the concept of OMA has matured into a well-established discipline within the area of modal testing [5]. The output of OMA is an estimate of the modal model for the whole system (i.e. the loading filter and the physical structure) which presents the challenge of separating the dynamic characteristics of the loading from the modal properties of the structure. The loads/excitation does not change the physical modes of the system [6], so if one can separate the noise modes from physical modes the accuracy of an OMA estimate is comparable to an EMA estimate. Furthermore, OMA lacks the ability to produce mass normalized mode shapes, however, both experimental techniques [7] and FE-based methods [8] have with success eliminated this shortcoming. The concept of automated OMA (i.e. OMA without any user interaction) enables the constant extraction modal features from any structure to be utilized in an SHM context. This makes OMA the obvious modal extraction technique within vibration-based SHM.

The scope of the present method is to localize and quantify damage, restricted to a limited number of candidate scenarios by merging operational modal parameter estimates with the system matrices of an FE model. Conceptually, the methodology is similar to a level 2–3 technique based on the sensitivity of experimentally obtained mass normalized mode shapes [9]. The differences are found in; 1) the current technique implements, via a parametric model, the idea of limiting the number of possible damage locations [10] and 2) the current method utilizes OMA to extract the modal properties. Both modifications increase the robustness and applicability to civil and larger mechanical structures, however, they also prompt the necessity of having an FE model of the monitored structure for mass normalization and prediction purposes. Damage detection techniques which use experimental modal data in combination with a parametric representation of the structure, falls into the category of model-based (or parametric) methods [11].

The experimental modal parameters are easily related to the properties of a parametric model, however the implementation of the FE model as well as the utilization of the model data vary substantially across the model-based techniques. Some methods synthesize a experimental measure for a change in flexibility to derive a forcing configuration to be subjected to an parametric model [12,13]. Methods based on FE model updating attempts to tune an FE model to the measured modal data using a predefined subset of adjustable parameters which are sensitive to damage [14–16]. The main drawback of these FE updating methods is the inverse-problem which often is ill-posed. This has prompted FE based methods which bypass the ill-condition issue by introducing statistical frameworks [17,18].

The damage identification technique presented in this paper is very closely related to the FE model updating methods listed above and features the same fundamental algebraic operation. Therefore the methods inherits some of the same challenges when dealing with limited, noisy data and a wide range of potential damage mechanisms. The current method does not attempt to fit a parametric model to test data but merely utilize FE model information in combination with measured modal data in the computation of the modal sensitivities - this is the most distinct feature of the present method in relation to other published model-based techniques. Since the reference data set and the modal sensitivities are based on measured data, the gap between the reference and "damaged" data can be assumed limited, hence no iterative process is necessary. Ultimately the proposed technique is able to locate and quantify damage given the structural modification is small and corresponds to a predefined scenario in one calculation step.

A successful application of the current method relies on the modal parameters being sensitive towards the predefined scenarios of structural change. The fundamental relations which found the basis of the method in combination with the implementation of the scenario idea enables an examination of the method usability. Therefore, this paper features a section which describes the preliminary considerations necessary to determine whether or not the current technique is feasible, with respect to a given structure and configuration of scenarios. On a more general level one might argue that the usability of using any modal-based technique to detect and locate specific candidate structural modifications is disclosed.

Lastly, the current method is demonstrated on a experimental test case where the structural modifications consist of local mass perturbations. Hence, the technique is demonstrated on damage cases in the form of mass increase only. In the test case the modal parameters are extracted with no user interaction and by means of a time domain identification technique.

2. Scenario-based approach using modal sensitivities

The mode shape and frequency sensitivity equations in the form presented by Heylen [19] founds the basis for the present technique. The undamped sensitivity or derivative of mode shape i with respect to a local change parameter u in the mass and stiffness matrix is given by

$$\frac{\partial \mathbf{b}_i}{\partial u} = -\frac{1}{2m_i}\mathbf{b}_i^T\frac{\partial \mathbf{M}}{\partial u}\mathbf{b}_i\mathbf{b}_i + \sum_{r=1,r\neq i}^{Nm}\frac{1}{\omega_i^2-\omega_r^2}\frac{1}{m_r}\mathbf{b}_r^T\left(-\omega_i^2\frac{\partial \mathbf{M}}{\partial u}+\frac{\partial \mathbf{K}}{\partial u}\right)\mathbf{b}_i\mathbf{b}_r \tag{1}$$