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Structural damage localization by outlier analysis of signal-processed mode shapes – Analytical and experimental validation

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ABSTRACT

Contrary to global modal parameters such as eigenfrequencies, mode shapes inherently provide structural information on a local level. Therefore, this particular modal parameter and its derivatives are utilized extensively for damage identification. Typically, more or less advanced mathematical methods are employed to identify damage-induced discontinuities in the spatial mode shape signals, hereby, potentially, facilitating damage detection and/or localization. However, by being based on distinguishing damage-induced discontinuities from other signal irregularities, an intrinsic deficiency in these methods is the high sensitivity towards measurement noise. In the present paper, a damage localization method which, compared to the conventional mode shape-based methods, has greatly enhanced robustness towards measurement noise is proposed. The method is based on signal processing of a spatial mode shape by means of continuous wavelet transformation (CWT) and subsequent application of a generalized discrete Teager–Kaiser energy operator (GDTKEO) to identify damage-induced mode shape discontinuities. In order to evaluate whether the identified discontinuities are in fact damage-induced, outlier analysis is conducted by applying the Mahalanobis metric to major principal scores of the sensor-located bands of the signal-processed mode shape. The method is tested analytically and benchmarked with other mode shape-based damage localization approaches on the basis of a free-vibrating beam and validated experimentally in the context of a residential-sized wind turbine blade subjected to an impulse load.

1. Introduction

Numerous vibration-based structural health monitoring (SHM) methods have been proposed for detection and/or localization of structural damages in aerospace, civil, and mechanical systems, see, for instance, [1–4]. Commonly, these methods are applied in such a way that a chosen damage feature, for example, direct kinematic response or modal parameters, from a current state is compared to the corresponding feature from the healthy reference state. In principle, the structure is potentially damaged if the chosen feature from the current state differs significantly from that of the reference state.

The applicability of the proposed damage detection and/or localization methods has primarily been tested on the basis of analytical models, finite element (FE) simulations, and controlled laboratory tests; all in which significant simplifications

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and idealizations are made with regard to, among other things, geometric boundary conditions, applied loads, and environmental effects. Here, it has been found that the simple methods directly comparing pre- and post-damage vibration-based quantities, such as modal parameters, exhibit only limited potential for damage detection and/or localization, see, for instance, [1,5]. Under more realistic conditions, these methods become completely inapplicable as the direct changes of the aforementioned quantities normally will be concealed by environmental effects and noise contamination. For instance, it is documented in [6,7] how environmental effects and general operational conditions can account for up to at least 5% shifts in eigenfrequencies, which, as documented in, for example, [7,8], cannot be expected to be exceeded by damage-induced eigenfrequency changes.

Due to the general inadequacy of the simple methods, current research within the field of vibration-based SHM is mainly focused on developing more sophisticated and robust methods. Some of these methods are based on signal processing of spatial mode shape signals, which seems auspicious as this modal parameter, contrary to global modal parameters such as eigenfrequencies, inherently provides structural information on a local level. A common approach is to exploit that a damage will introduce mode shape discontinuities, albeit not always directly visible ones, which can be captured by use of signal processing techniques, for example, continuous wavelet transformation (CWT). CWT has been utilized extensively for localizing structural damages in both simple beam- and plate-like systems, see, for example, [9–11], and more complex structures such as wind turbine blades [8,12,13]. However, by being based on distinguishing damage-induced discontinuities from other signal irregularities, an intrinsic deficiency of these CWT-based methods is the rather low robustness towards measurement noise. In order to treat this issue, a method in which wavelet-transformed mode shapes are processed by use of the discrete Teager–Kaiser energy operator (DTKEO) is proposed in [14]. Here, it is shown, on the basis of analytical and experimental work with different beams, that by adding the DTKEO, the robustness towards noise is significantly enhanced and in general more unambiguous localization results are obtained.

One of the major advantages of the method proposed in [14] is the lack of need for baseline mode shape signals, that is, signals from the healthy structural state. This, however, also means that the discrimination between potentially damaged locations and undamaged ones is based solely on direct, deterministic inspection of the signal-processed mode shapes from the current state; an approach that, as will be demonstrated in the present study, can be impossible in some particular cases. Consequently, the authors of the present paper have proposed a further development of the aforementioned method, in which the DTKEO is expanded to a generalized DTKEO (GDTKEO) by use of a lag parameter, κ, and where outlier analysis is added to yield the final discrimination between undamaged and damaged areas by use of signals from both the healthy (baseline) and the current state [15]. Regarding the constraint of needing baseline mode shape signals, it is noticed that, according to numerous studies, for instance, [16], it is problematic since a priori measurement in a healthy condition is affected greatly by environmental and operational variability. However, when statistical evaluation is applied, a baseline model representing the healthy state is derived on the basis of several measurements, hereby including the variability in the mode shape signals and, thus, making the baseline model applicable for classifying mode shape signals from the current structural state.

By applying the method proposed in [15] to experimental setups, it has been found that the approach depends too much on the number of measurement points. Therefore, in the present paper, we propose a method that can be regarded as the final edition of the preliminary one documented in [15]. As such, the method proposed in the present paper constitutes a twofold refinement; firstly, the premise of selecting κ in the GDTKEO is changed in order to reduce the dependency on the amount of measurement points, and, secondly, the Mahalanobis metric is used in the statistical evaluation instead of T^2-statistics. The proposed method is composed of the following three steps: a filtered mode shape derivative is obtained of a spatial mode shape signal through CWT, and subsequently a generalized discrete Teager–Kaiser energy operator (GDTKEO) is applied to this derivative to form an energy-processed signal in which the damage-induced discontinuities are magnified. Finally, a statistical evaluation scheme based on the Mahalanobis metric is applied to principal scores of these energy-processed, filtered mode shape derivatives in order to label the structure as healthy or damaged at each sensor location/measurement point. To test the applicability of the method, and to justify this refinement of the preliminary method proposed in [15], two application examples of engineering interest, namely, an analytical beam model and experimental work with a residential-sized wind turbine blade, are treated.

The paper is organized as follows: in Section 2, the proposed damage localization method is presented, and in the following section, the method is applied in the two application examples. Here, the localization performance is compared to those yielded by the application of well-known mode shape-based damage localization methods in order to benchmark the method. Finally, some concluding remarks are presented in Section 4.

2. Methodology

Several aspects of the methodology have already been described by the authors in [15]. These aspects are, however, still included in the present section for the sake of completeness.

2.1. CWT

Since the fundamentals of the CWT and its applicability in damage identification, primarily as a signal discontinuity scanner, is well documented in numerous publications, see, for instance, [8–13,17], only the most relevant CWT aspects will be presented in this paper.

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