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A baseline-free structural damage indicator based on node displacement of structural mode shapes

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ABSTRACT

Most widely studied Structural Health Monitoring methods need baseline data from the undamaged state and a high number of sensors attached to the structure, which makes these methods difficult to be applied in real structures for on-line monitoring. In order to deal with that, the NOde DISplacement (NODIS) method is proposed by considering the structural damage indicator. The idea of the present work is to develop a baseline-free damage location and quantification method based on the node displacement of structural mode shapes. The damage location procedure is developed by combining the nodes from different mode shapes and the damage quantification is achieved by the proposed Transfer-Function-based Damage Indicator (TFDI). The advantages of this method are: (1) baseline-free, in terms of the comparison with a reference signal is not needed, (2) only a relatively small number of sensors is required for real-time damage location and (3) with the proposed TFDI, the damage detection result can be quantified. In the present paper, the baseline-free damage location algorithm is proposed and validated on a steel beam with an analytical model, a numerical model and experiments. In addition, the influence of temperature, the additional weight of the sensor and the error in sensor location on the NODIS method are studied. After that, the TFDI is developed and improved for the experiment. Finally, the method is applied to a supporting structure of a sailplane under complex boundary condition and different environmental temperatures.

1. Introduction

Structural Health Monitoring (SHM) has become one of the most important topics for structural aircraft engineers due to its benefits in enhancing safety, lightweight and reducing life-cycle cost [1–5]. Among all the SHM technologies, the vibration-based methods have shown to be promising [6–11]. These methods are proposed based on the idea that the existence of structural damage will lead to changes in the modal parameters, such as natural frequency, mode shape and modal damping values. In this paper, the vibration-based methods are reviewed in two categories: baseline-dependent methods and baseline-free methods.

Frequency-based methods identify the changes in the natural frequency between intact and damaged structure which are typical baseline-dependent methods. This response quantity is one of the earliest vibration information to be used for damage detection [12]. On the other hand, some researchers [13] show that mode-shape-based methods are more sensitive to local

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damages than frequency-based methods, because mode shape can represent the information along the whole structure. Similar to the frequency-based methods, mode-shape-based methods also compare the differences between the measured mode shape and the baseline mode shape. Hamey et al. [14] used mode shape curvature, which takes the second derivative of the mode shape, to detect delamination in a composite beam, as this method is more effective to small damages. Similar to mode shape curvature, some researchers used modal strain energy as a damage indicator [15–17]. Recently, Xu et al. [18] proposed a damage detection method based on longitudinal vibration shapes to locate two edges of a damaged section on an aluminum bar. Ciambella and Vestroni [19] introduced a filtering procedure for modal curvatures to locate damage more effectively. Anastasopoulos et al. [20] used a peak-shift algorithm to identify the modal strain on a steel I-beam with FBG sensors. All the mentioned methods need to record baseline data on the pristine condition. Thus, baseline-dependent methods require a large number of data storage. In addition, the real-time monitored signal cannot be directly translated to the health information of the structure which makes this method hard to be applied for on-line monitoring.

Due to the aforementioned problems, a lot of researchers focus on the techniques which allow damage detection without using past measured baseline data. Here, the baseline-free damage detection means to quantify damage without additional measurement of or comparison with the signals at the initial state under the different time-varying environment (e.g. temperature, load case and material degradation). Some researchers also agree that a method can be still considered as baseline-free, when no past measured baseline data is needed, in spite of using some “prior knowledge” [21]. Ratcliffe [22] proposed a gapped smoothing method (GSM) method in order to fit a higher order polynomial of the measured mode shape curvature from a damaged 1-D structure. The curved fit curvature generated by the GSM method represents the baseline. Later on, this method is adopted into more complex structures, such as composite plate [23] and metallic sandwich panel with truss cores [24]. Zhong et al. [25] introduce a stationary wavelet transform (SWT) -based method to investigate the differences in left and right half of the mode shape. The SWT coefficients are considered as a better crack indicator. The main idea of these methods is to use the changes or lack of smoothness in mode shape or mode shape curvature due to damage. However, these methods still need a large number of sensors to construct the mode shape and the accuracy of damage detection is restricted by the number of the accelerometers for the mode shape measurement, which make these methods not efficient for real-time health monitoring.

Some researchers also found that the position of the nodal points (also referred as nodes) in a particular mode shape at its corresponding natural frequency can be altered by damage. Wolff and Richardson [26] found that the position of the node will change when removing the bolt on an aluminum flat plate with a bolted rib stiffener. Dilena and Morassi [27] investigated this method on a free-free beam in bending vibration. Nevertheless, the method they proposed requires multiple impact hammer modal tests on the structure to locate the nodes by investigating the phase angle changes sign in two neighboring points and further identify the movement of the node. This makes the method time consuming and difficult to be applied for on-line monitoring.

However, the vibration amplitude at the nodes can be derived into an efficient Structural Damage Indicator (SDI), since it represents the change of structural behavior due to damage. Different from common damage indicators which extract features from the measured signal only, the SDI is defined by considering the structure response quantity influenced by damage directly. With the SDI idea, the monitored signals are not compared with the measured signal at the pristine stage but with a mechanical property of the (theoretically) ideal structure. In addition, the SDI at the initial state or the first measurement can be considered as an intrinsic quality assurance. In common baseline-based SHM methods, the first measurement does not give any information about the structure’s state of health but only defines the reference state which is usually called baseline. In the proposed method, the first measurement directly gives information about the health stage of the structure and, therefore, can be seen as a kind of intrinsic quality assurance. The structural response quantity can be but not limited to the shift of neutral axis [28], high tension stresses in plate due to the post-buckling regime [29] and the shift of nodal points in mode shape [26]. The numerical models which are already developed in the sizing process can be used to investigate the structural behavior in the early stage. Since the critical damage will have a significant influence on the structural behavior regardless of the environmental changes and the material degradation, the SDI is considered to be stable and efficient.

Little attention is paid to use the vibration response at the nodes for damage detection. As it will be shown, the vibration amplitude at the nodal points has the potential to be applied to develop a baseline-free on-line damage detection method [30]. In this paper, a baseline-free damage location method based on the lateral displacement at nodes in flexural vibration mode shape is proposed for real-time damage detection. This method is identified as NOde DISplacement (NODIS) method. In order to achieve damage location and quantification with a small number of sensors, a damage location procedure which combines the nodes of two mode shapes is developed for the NODIS method. In addition, a Transfer-Function-based Damage Indicator (TFDI) is proposed to quantify the damage detection result. The method is validated with saw cut and then used to monitor a complex structure under simulated time-varying environment. Furthermore, the influence of the sensor weight is also studied.

This paper is organized as follows. Section 2 explains the principle of the proposed NODIS method. A damage location algorithm is proposed based on the influence of the damage on the displacement of nodes. In addition, the mechanism of baseline-free is explained. Then, the temperature-induced load and boundary conditions are discussed. In Section 3, the NODIS method is validated with a numerical model and experiment. In the experiment, the TFDI is proposed to normalize the damage detection result. The performance of the method is studied with saw cuts. Furthermore, the damage location procedure, the influence of the sensor weight and the influence of error in sensor location are studied. In Section 4, the method is applied for damage detection in a retractable supporting structure for a sailplane under complex boundary condition and different environmental temperatures. Finally, the work is concluded in Section 5.