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Comprehensive comparison of macro-strain mode and displacement mode based on different sensing technologies

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ABSTRACT

A comprehensive comparison of macro-strain mode and displacement mode obtained from distributed macro-strain sensing and high-density point sensing (such as accelerometers) technologies is presented in this paper. Theoretical derivation reveals that displacement mode shape from accelerometers and modal macro-strain from distributed macro-strain sensors can be converted into each other. However, it is realized that displacement mode shape as global behavior of a structure can still be calculated with high-precision from modal macro-strain considering measurement errors in practical monitoring, whereas modal macro-strain can hardly be accurately achieved from displacement mode shape when signals are corrupted with noise in practical monitoring. Simulation and experiment results show that the calculated displacement mode shapes are very close to the actual ones even if the noise level reaches 5%. Meanwhile, damage index using measured modal macro-strain is still effective when the measurements are corrupted with 5% noise which is reliable for damage detection in practical monitoring. Calculating modal macro-strain from noise-polluted displacement mode shape will cause an unacceptable error if the noise level reaches only 0.5%, which has been verified in the simulation.

1. Introduction

Structural health monitoring (SHM) becomes more and more important and most of the large-scale structures (bridges, buildings, tunnels and so on) have been installed with structural health monitoring systems (SHMS). The functions of SHM can be categorized: (1) performance validation of large-scale complicated structures and safety assurance; (2) efficiency and accuracy improvement of structural maintenance; (3) health status evaluation and prediction for lengthening the service life of structures; (4) real-time information collection and rapid diagnosis of disaster and post-disaster. A SHM-based performance assessment technique can not only identify damage at the early stage but also evaluate damage extent so that the owners can make use of such information to optimize maintenance and retrofitting program at lowest cost [1].

Vibration-based SHM techniques have gained considerable attention due to rise in demands for rapid assessment of structural safety and performance against inevitable degradation. Structural performance deterioration results in the changes of dynamic characteristics (natural frequencies, mode shapes, modal damping ratios and so on). In the light of these

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changes, a number of performance assessment techniques have been successfully proposed, for example, change of frequency, modal assurance criterion (MAC), modal stiffness, modal flexibility, modal strain energy, frequency response function (FRF) and its curvature. Extensive literature reviews about vibration-based SHM methods have been reported by [2–5].

Above-mentioned vibration-based SHM methods have been explored to use the dynamic measurements to evaluate the structural global behaviors and local behaviors. Global behaviors are often reflected by dynamic displacement, frequencies, displacement mode shapes which can be directly obtained by point sensors such as accelerometers, velocimeters or displacement transducers. Meanwhile, a number of vibration-based methods have been developed to make use of dynamic responses to reflect local behaviors of structures. Some challenges still confront practicality of using dynamic responses to evaluate the local behaviors of structures (damage identification and local stiffness identification). On one hand, frequency holding high measuring precision is too global to identify local damage [6–8], whereas damage indices such as modal flexibility, modal energy which are theoretically sensitive to damage are also sensitive to measurement errors [9]. On the other hand, strain as a local measurement has been verified to be more sensitive to damage. Strain-based indicators for structural damage identification are reviewed in [10]. However, traditional strain gages can reflect the influence of damage effectively only when the gage covers the damage region. Meanwhile, strain of the regions near the damaged zones may decrease, which will fail to identify damage. As a result, the point strain sensors are not quite suitable for the large-scale civil engineering structures, and it is urged to explore some new types of distributed and long-gauge strain sensors.

Under this background, distributed sensing and actuating concept have attracted considerable attention in structural health monitoring and vibration control. Passive vibration control using distributed piezoelectric transducers is investigated in [11]. Vidoli and Dell'Isola [12] used the uniformly distributed PZT actuators in vibration control of plates and Andreaus et al.[13] have developed piezoelectric passive distributed controllers for beam flexural vibrations. Damage localization in plate-like structure using built-in PZT sensor network has been presented in [14]. Other literature about piezoelectric transducers can be found in [15–19].

Inspired by the distributed sensing of piezoelectric transducers, Li and Wu [20] have developed a feasible implementation of distributed long-gauge fiber Bragg grating (FBG) sensing techniques to utilize the strain distributions throughout the full or critical regions of structures to detect the arbitrary and unforeseen damage. Hong et al. [21] investigated the method of extracting modal macro-strain from distributed macro-strain responses under ambient excitation. These techniques propose a promising novel alternative due to the high sensitivity to local damage and the potential to catch global structural information by utilizing "distributed" sensors placement.

On the basis of preceding efforts on the development of distributed sensing, a comprehensive comparison of macro-strain mode and displacement mode using distributed macro-strain sensing and high-density point sensing technologies is presented in this paper. Theoretical derivation reveals that displacement mode shape from accelerometers and modal macro-strain from distributed macro-strain sensors can be converted into each other. However, it is realized that displacement mode shape as global behavior of a structure can still be calculated with high-precision from modal macro-strain considering measurement errors in practical monitoring, whereas modal macro-strain can hardly be accurately achieved from displacement mode shape when signals are corrupted with noise in practical monitoring. Simulation and experiment results show that the calculated displacement mode shapes are very close to the actual ones even if the noise level reaches 5%. Meanwhile, damage index using measured modal macro-strain is still effective when the measurements are corrupted with 5% noise which is reliable for damage detection in practical monitoring. Calculating modal macro-strain from noise-polluted displacement mode shape will cause an unacceptable error if the noise level reaches only 0.5%, which has been verified in the simulation. Damage index using calculated modal macro-strain is also sensitive to noise, so it is effective for structural health monitoring only when displacement mode shape is measured with high-accuracy.

2. Theory background

Distributed long-gauge sensing techniques are characterized by their capacity to obtain the measurements by integrating both local and global information. This capacity arises because strain is a typical local response, and distributed sensor placement helps to record strain responses covering a large region of a structure. The principle of modal macro-strain proposed by [22] is introduced below.

For a beam structure with two local DOFs at each node (see Fig. 1, macro-strain $\overline{\varepsilon}_m$ from mth long-gauge sensor can be expressed at time domain and frequency domain as

$$\overline{\varepsilon}_m(t) = \frac{h_m}{L_m}\left[v_i(t) - v_j(t)\right] \tag{1}$$

$$\overline{\varepsilon}_m(\omega) = \frac{h_m}{L_m}\left[v_i(\omega) - v_j(\omega)\right] \tag{2}$$

in which h_m is the distance from the mth strain sensor to the neutral axis, L_m is the gauge length of the mth sensor, and $v_i(\omega)$ and $v_j(\omega)$ represent rotational displacement of ith and jth nodes in the frequency domain, respectively.