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Quasi-optical coherence vibration tomography technique for damage detection in beam-like structures based on auxiliary mass induced frequency shift

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ABSTRACT

A novel quasi-optical coherence vibration tomography (Quasi-OCVT) measurement system suitable for structural damage detection is proposed by taking the concept of two-dimensional optical coherence vibration tomography (2D-OCVT) technique. An artificial quasi-interferogram fringe pattern (QIFP) similar to the interferogram of 2D-OCVT system, as a sensor, was pasted on the surface of a vibrating structure. Image sequences of QIFP were captured by a high-speed camera that worked as a detector. The period density of the imaged QIFP changed due to the structural vibration, from which the vibration information of the structure could be obtained. Noise influence on the measurement accuracy, torsional sensitivity and optical distortion effect of the Quasi-OCVT system were investigated. The efficiency and reliability of the proposed method were demonstrated by applying the system to damage detection of a cracked beam-like structure with a roving auxiliary mass. The roving of the mass along the cracked beam brings about the change of natural frequencies that could be obtained by the Quasi-OCVT technique. Therefore, frequency-shift curves can be achieved and these curves provide additional spatial information for structural damage detection. Same cases were also analyzed by the finite element method (FEM) and conventional accelerometer-based measurement method. Comparisons were carried out among these results. Results obtained by the proposed Quasi-OCVT method had a good agreement with the ones obtained by FEM, from which the damage could be directly detected. However, the results obtained by conventional accelerometer showed misleading ambiguous peaks at damage position owing to the mass effect on the structure, where the damage location cannot be identified confidently without further confirmation. The good performance of the cost-effective Quasi-OCVT method makes it attractive for vibration measurement and damage detection of beam-like structures.

1. Introduction

Health monitoring and damage detection of structures are important not only for the leading safe operation but also for retaining structural performance. When a structure suffers from damages, one or more of its dynamic properties will change.

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Conversely, the damage could be identified using the changes in the structural dynamic response characteristics. Very good reviews on these issues have been presented by Dimarogonas [1], Salawu [2], Wei et al. [3], Daniele et al. [4] and Jassim et al. [5]. Generally, the damage identification methods can be categorized as natural frequency-based methods, mode shape-based methods, curvature/strain mode shape-based methods and other methods based on changes in the modal parameters or changes in the dynamic response [3]. The most useful damage detection and localization methods are probably those using changes in natural frequencies because frequency measurements can be conveniently conducted, less contaminated by experimental noise and often reliable.

A number of studies also have been carried out to develop crack identification algorithms in different scenarios (e.g., single damage and multiple damages). Most studies concerning the problem in beams deal with a single crack. Some investigators consider that a crack reduces the section modulus (EI) of a small segment around itself [6–8]. Others consider that a crack causes a local discontinuity in the slope of the deflection curve or reduces the energy content of the beam [9]. Kaushar et al. [10] and Rizos et al. [11] have represented the crack as a rotational spring in a cantilevered beam having a rectangular cross section. For methods based on overall structural frequencies, abnormal loss of stiffness in inferred when the measured natural frequencies are substantially lower than expected. However, it could be necessary for a natural frequency to change around 5% for damage to be detected with confidence [12]. The main disadvantage of using natural frequency changes for crack detection is the fact that significant cracks may cause small changes in natural frequencies, and therefore may go undetected due to the measurement errors [13]. In addition, methods based on overall structural frequencies required either postulated correct vibration models of damage or natural frequencies of the intact structure before undertaking physical measurements. These methods are thus limited in application to specific structural geometries and type of the assumed damage model. Utilization of a theoretical damage model could introduce uncertainties into the results: methods that rely on measured data without any prior theoretical assumptions would be more appropriate to large civil engineering structures. Zhong et al. [14–16] proposed an approach based on auxiliary mass spatial probing to provide a method for crack detection in beam-like structure. Success of the method depends on both precise positioning of the auxiliary mass and identification of accurate natural frequencies of the test structures. Recently, Wang et al. [17] introduced a novel concept called FREquency Shift (FRESH) path to describe the dynamic behavior of structures with auxiliary mass. Nguyen [18] presented the influence of a concentrated mass location on the natural frequencies of a cracked double-beam.

Generally, modal parameters such as natural frequency can be obtained easily from measured vibration responses. Techniques currently available for vibration measurements can be classified as contact-type and noncontact-type. Contact-type sensors, e.g., accelerometers, often have limitations in practical applications due to the physical connection or to extra mass loading on the structure. The noncontact-type technique can realize accurate non-intrusive dynamic monitoring and the results will not be affected by errors due to extra mass loading, which seems to be relevant for modal parameter estimation, especially when testing light or small structures. Noncontact vision-based vibration measurement systems have been developed recently. Jaka et al. [19] proposed a simplified gradient-based optical flow method for subpixel displacement measurement. Busca et al. [20], Ribeiro et al. [21] and Feng M et al. [22] developed vision-based displacement measurement systems to measure the displacement of the bridges by tracking the natural or artificial targets on the structural surface using different algorithms, including pattern matching, edge tracking and object-search methods.

Recently, the authors proposed 1D- and 2D-optical coherence vibration tomography (OCVT) techniques [23–26]offering the possibility of performing high resolution and non-intrusive vibration measurements. In the 2D-OCVT system [24], the vibration information was obtained from the interferogram that vary with the change of the distance between the surface of a reference mirror and the tested object. In the present work, a quasi-optical coherence vibration tomography (Quasi-OCVT) system was inspired on the principle of the 2D-OCVT system, which can realize vibration measurements and damage detection by using quasi-interferogram fringe patterns (QIFP) as a sensor and a high-speed CMOS image sensor (CIS) camera as a detector. The proposed method is firstly applied to the damage detection and localization of a cantilevered beam with a single crack, which helps verifying the accuracy and effectiveness of the Quasi-OCVT technique.

2. Theoretical background

2.1. Principle of the Quasi-OCVT technique

In a 2D-OCVT system [24], a series of interferograms was recorded during the vibration of a structure. The fringe pattern density of the interferogram changed when the structure was vibrating and this change could be used for real-time structural dynamical characterization. Taking the concept from the 2D-OCVT, a quasi-interferogram fringe pattern (QIFP) that looks similar to the real interferogram has been designed. Fig. 1(a) shows an interferogram (the upper one) from the 2D-OCVT system and an artificial QIFP (the lower one) that will be attached to the surface of a vibrating structure as a sensor. The intensity distribution of the QIFP, $I(x)$, can be expressed as

$$I(x) = 1 + V\cos(\varphi + 2\pi dLx) \tag{1}$$

where x is the horizontal axis corresponding to the length of the QIFP, V is the contrast of the QIFP, φ is the initial phase, d is the period density of the QIFP and L is the physical length of the QIFP. Note that the fringe pattern period density is defined as the number of fringe period per unit length.