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Identification of structural stiffness and excitation forces in time domain using noncontact vision-based displacement measurement

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ABSTRACT

The emerging noncontact vision-based displacement sensor system offers a promising alternative to the conventional sensors for quantitative structural integrity assessment. Significant advantages of the noncontact vision-based sensor include its low cost, ease of operation, and flexibility to extract structural displacement responses at multiple points. This study aims to link the measured displacement data to the quantification of the structural health condition, by validating the feasibility of simultaneous identification of structural stiffness and unknown excitation forces in time domain using output-only vision-based displacement measurement. Numerical analysis are first carried out to investigate the accuracy, convergence and robustness of identified results to different noise levels, sensor numbers, and initial estimates of structural parameters. Then, experiment on a laboratory scaled beam structure is conducted. Results show that the global stiffness of the beam specimen as well as external hammer excitation forces can be successfully and accurately identified from displacement measurement at two points using one camera. The proposed output-only time-domain identification procedure utilizing vision-based displacement measurement represents a low-cost method for either periodic or long-term bridge performance assessment.

1. Introduction

Degradations in structural materials or geometric properties may greatly affect structural safety. During the past two decades, a considerable amount of researches have been conducted in the area of structural health monitoring (SHM) for objective and quantitative structural integrity assessment [1]. Particularly, due to increasing traffic volumes, concerns and needs arise to assess structural conditions of the aging and deteriorating network of highway bridges. However, conventional visual practice is inadequate to inspect the overwhelming number of bridges, or address their needs for maintenance and management. Nondestructive evaluation (NDE) has shown potentials for detecting hidden damage and more objective assessment, but bridges' spatially large size presents a significant challenge to implementing such technologies. Like visual inspection, NDE often detects local flaws without an ability to efficiently assess bridges' overall structural conditions.

Hence, vibration-based SHM techniques have been widely investigated, categorized as the time-domain method and frequency-domain method. All these methods have achieved satisfactory performance for both numerical and experimental

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Table 1
Comparison of sensors for measuring structural vibration.

Sensors	Measure	Pros	Cons
Wired or Wireless Accelerometer	• Acceleration	• Suited for continuous monitoring • Hardware easily available • Sensitive to high-frequency vibration	• High cost of sensor system • High cost of installation & sensor system maintenance • Contact sensor • Single-point measurement • Adding mass or stiffness to structure
LVDT	• Displacement	• Hardware easily available	• Difficult & costly to install • Contact sensor • One-dimensional measurement • Single-point measurement
Laser Vibrometer	• Velocity or displacement	• Noncontact • More accurate high-frequency displacement measurement • Perform global measurement using scanning laser vibrometer	• High equipment cost • Not suited for continuous monitoring
Vision-based displacement sensor	• Displacement	• Noncontact • Low-cost industrial or consumer-grade video cameras • Continuous monitoring • 2- or 3-dimensional measurement • Flexible & multiple measurement points on visible object surface	• Measurement error due to heat haze and ground motion • Measurement error in dim light • Optical noise • Accuracy deteriorates for multi-point measurements over a wider field of view

studies [2–10]. However, the requirement for installing dense point-wise sensor (e.g., accelerometers, strain gauges, LVDT, etc.) networks can be a downside as it would take considerable measurement cost, time and effort, and traffic disruptions. Therefore, although recent researches have demonstrated some maturity for vibration-based SHM, implementation of conventional on-structure sensors for structural assessment has been hindered to some extent. As an emerging noncontact method, the vision-based displacement sensor systems offer a promising alternative, which are primarily enabled by different subpixel image template matching/registration techniques. In contrast to the extensively used point-wise sensors, the vision sensor can be termed as a noncontact distributing sensing technique as displacements of a large number of points can be extracted from the captured video images by one camera. It can either be used as a substitute for conventional sensors or integrated with these sensors in the SHM system. A comparison between commonly used vibration sensors and the vision-based displacement sensor are summarized in Table 1.

Recent studies on vision-based displacement sensors by different research groups have experimentally demonstrated that high accuracy can be achieved for both single-point and multi-point structural displacement measurement by either tracking high-contrast predesigned target panels or natural features on the structural surface [11–28]. For example, Khuc and Catbas [26] developed a vision-based displacement measurement method by tracking natural structural features. A practical unit conversion method was proposed based on the camera calibration technique. The measurement accuracies of the vision sensor for displacement responses and modal parameters for a football stadium are compared with those from reference LVDTs and accelerometers, respectively, for various conditions such as changing ambient light and distance to monitoring location. However, study of the vision-based application is still at an early stage. A most recent state-of-the-art review revealed that current applications of vision sensors are mainly focusing on measuring single-point or full-field displacements, as well as obtaining operational deflection shapes for various structures [29]. There have been some studies towards linking the measured displacement data to structural safety condition [30–36]. For example, Catbas et al. [32] presented a methodology for bridge load rating by integrating computer imaging with traditional sensor technology. Baqersad et al. [37] used a new expansion approach to extract the full-field dynamic strain on a wind turbine from measured displacement at discrete locations by a pair of high-speed cameras. Wang et al. [38] presented new techniques for vibration mode shape recognition using image processing and pattern recognition. A variety of shape descriptors (i.e., the Zernike moment descriptor, Fourier descriptor and wavelet descriptor) with the capability of recognizing mode-shape differences were described. Chen et al. [33] validated vision-based modal identification through laboratory tests by high-speed video using motion magnification. Dworakowski et al. [34] obtained the deflection curve of small-scale laboratory beams by means of digital image correlation (DIC). Then two deflection shape-based algorithms are evaluated for damage detections of the beams. Feng and Feng [39] proposed a time-domain method to identify the equivalent stiffness of a railway bridge based on vision-based displacement measurement with the prerequisite of known trainloads. Sensitivity studies showed that train-induced displacement response is more suited than acceleration responses to identify the bridge stiffness. Song et al. [40] presented a proof-of-concept application of virtual vision sensor for damage localization in laboratory steel cantilever beams. Kim et al. [41] proposed a vision-based monitoring system using DIC to evaluate the cable tensile forces of a cable-stayed bridge. Yong et al. [42] and Oh et al. [43] respectively conducted laboratory vibration experiments on frame structures. Modal parameters are identified and compared with those from the conventional accelerometer-based method, which show good agreement. Moreover, using the identified modal parameters, Feng and Feng [12] successfully updated the