Mechanical Systems and Signal Processing 60-61 (2015) 571–582

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Target-less computer vision for traffic signal structure vibration studies

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ARTICLE INFO

Article history:
Received 25 October 2013
Received in revised form
21 May 2014
Accepted 6 January 2015
Available online 19 February 2015

Keywords:
Vibration
Modal testing
Structure dynamics
Computer vision
Target-less

ABSTRACT

The presented computer vision method allows for non-contact, target-less determination of traffic signal structure displacement and modal parameters, including mode shapes. By using an analytical model to relate structural displacement to stress, it is shown possible to utilize a rapid set-up and take-down computer vision-based system to infer structural stresses to a high degree of precision. Using this computer vision method, natural frequencies of the structure are determined with accuracy similar to strain gage and string potentiometer instrumentation. Even with structural displacements measured at less than 0.5 pixel, excellent mode shape results are obtained. Finally, one-minute equivalent stress ranges from ambient wind excitation are found to have excellent agreement between the inferred stress from strain gage data and stresses calculated from computer vision tied to an analytical stress model. This demonstrates the ability of this method and implemented system to develop fatigue life estimates using wind velocity data and modest technical means.

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1. Introduction

Structural vibrations from live and environmental loads constitute a mechanism for fatigue failure due to cyclic stresses developed within the excited structure. Vibrating structures generally exhibit multiple natural frequencies and shapes of deformation corresponding to each frequency. Traffic signal structures are excellent examples of ambient wind-excited, flexible structures, and have been extensively studied [1–11]. Cyclic strains are observed at the connections of traffic signal structures due to wind-induced excitation. Such vibrations occur both vertically and horizontally as a result of vortex shedding, natural gusts, truck-induced gusts, and other effects [2,6–11]. As a result of these repetitive strains, connections within the structure often exhibit a reduced fatigue life. While the fatigue failure of traffic signal structures does not realize a significant portion of traffic accidents or deaths, concern is highlighted due to the apparent unpredictability of this hazard to motorists and the economics of replacing fatigued traffic signal structures [2]. Unfortunately, experimental analysis of structural response is often difficult or costly to employ because current methods generally require large arrays of instrumentation [12–19]. For structures such as high mast illumination poles [17], application of instrumentation presents a risk for injury. Current technology available to monitor traffic signal structure response includes infrared camera-emitter systems, fixed linear displacement sensors, accelerometers, and strain gages [1,3–11].

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http://dx.doi.org/10.1016/j.ymssp.2015.01.005
0888-3270/Published by Elsevier Ltd.

Computer vision-based techniques offer an alternative experimental analysis method and have been used for the analysis of structural motion for many years [20–23]. Computer vision is based on research into artificial intelligence and is closely related to pattern recognition [24]. The main benefit of a computer vision-based technique is the inherently non-contact approach. Short term studies or analyses of hard-to-access structures can be performed in situations where traditional instrumentation would be infeasible.

One prominent example of a computer vision-based analysis of a bridge measured the static and dynamic response due to car traffic [20]. This experiment provided a strong proof-of-concept for computer vision methods of analysis for civil engineering structures. However, the non-contact benefits of computer vision techniques were negated by the necessity of installing targets, where the accuracy of the analysis was noted to be highly dependent upon the target geometry.

Target-less analysis of bridge dynamic responses using consumer-grade cameras has been performed [23]. This approach utilized edge detection and pattern matching algorithms in combination, initially on specialized targets, but noted that without a target, measurement reliability was strongly influenced by the contrast at the point of analysis [23]. Edge detection and cross-correlation algorithms have been more commonly used due to their relatively low computational demand. However, these algorithms are generally less robust than pattern recognition algorithms [23,25]. A robust algorithm is denoted by its broad applicability and lack of dependence on well- or pre-defined geometry for a target.

While edge detection algorithms are usually not robust enough to permit tracking of any given target geometry, researchers have been able to analyze damage in structures by determination of bridge mode shapes using a wavelet-based edge detection technique [21]. This presented a novel use of an algorithm for determination of mode shapes to a high degree of accuracy. More importantly, this technique did not require the placement of targets on the structure of interest. The researchers noted, however, that the presence of any edges in the image background, such as separated clouds, tended to distort the mode shape obtained by edge detection.

Computer vision-based measurement has also been successfully applied to wind turbines, resulting in effective determination of mode shapes. This approach utilized a packaged, point-tracking software with specialized cameras [22]. While this presented an example of the general application of a computer vision method for modal analysis, the need to attach specialized targets negated the non-contact benefits associated with a computer vision-based approach.

In order to generalize a computer vision method for broader application to experimental analysis of structures, it is necessary to develop an approach which does not require specialized targets or geometry. Through utilization of a robust pattern recognition algorithm, the application of computer vision-based techniques will not be limited to analysis at structural points amenable to the attachment of targets. The minimum quadratic difference (MQD) algorithm presents a robust method of analysis for determining dynamic characteristics and displacement time series of flexible structures.

Using a non-contact, target-less computer vision based on the MQD algorithm, the objectives of this research are to (1) develop and validate a method to determine structural displacements, (2) develop and validate a method to infer structural stresses, (3) validate a method to determine the dynamic characteristics of a structure, and (4) apply the developed method to infer stresses due to ambient wind-induced excitation.

This paper details the traffic signal structure of interest and the methods for obtaining data (Section 2). The validity of MQD-based computer vision is then analyzed for structural displacement measurements and stress inference (Section 3). This method is then applied to determine the dynamic properties of the structure (Section 4). Using the developed stress inference method, MQD-based computer vision is used to relate structural response to wind speed during wind excitation (Section 5). The findings are then discussed and concluding remarks are made (Sections 6 and 7).

2. Experimental structure and measurement techniques

The combination of a wealth of previous research into traffic signal structure dynamic responses and the relatively large displacements realized during vibration makes traffic signal structures excellent candidates for dynamic response analysis using a computer vision-based method. As examples of flexible structures which are excited by ambient wind, traffic signal structures easily undergo vibration, with damping ratios generally less than 1% and fundamental frequencies of approximately 1 Hz [7].

Traffic signals are generally supported by a vertical pole and horizontal mast arm which jointly constitute a cantilevered traffic signal structure. The vibrations of these structures are categorized as in-plane (IP) for vertical vibrations and out-of-plane (OOP) for vibrations parallel to the direction of vehicles passing under. The full-scale traffic signal structure of interest is depicted in Fig. 1a. The structure was located at Texas A&M University's Riverside Campus with an orientation depicted in Fig. 1b.

A Firstmark Controls 160-0963-S6SS string potentiometer was used to directly measure mast arm tip displacement. The string potentiometer was powered by an Agilent A3611A power supply, and output voltage was recorded using a Tektronix TDS3034B oscilloscope at a sampling frequency of 100 Hz. A Sokki Kenkyujo AWC-8B-11-3LT weldable strain gage was installed near the base of the pole as depicted in Fig. 1d, and sampled at 100 Hz by a StrainBook/616 DAQ to measure the strain associated with IP base bending moment. The data was recorded to a laptop onsite.

Video was captured with a SONY HDR-CX220 consumer-grade video camera with a 1280×720 pixel resolution and a sampling rate of 29.97 Hz. Note that the 30 Hz sampling rate effectively limited this setup to capture modes of 15 Hz or less due to the Nyquist frequency criterion. The camera was situated at a ground distance of 41.3 m from the closest point on the structure. For every test except ambient excitation, a scale factor of 13.2 mm/pixel was chosen based upon the measurement of five geometries in the field of view (Fig. 1a). This factor was used to scale measured displacements from pixels to physical