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Non-contact vibration measurement of cables in a cable-stayed bridge by consumer-grade camera

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ABSTRACT: Cable tension is a crucial factor in determining the overall condition of a cable-stayed bridge structure. One simple and important method for cable tension estimation is using natural frequency from vibration measurement. Traditional vibration measurement is through accelerometers which requires direct access to cables for sensor installation as well as multiple sensors to cover all the cables of interest. Thus this kind of vibration monitoring for bridge inspection will be expensive and time consuming. To overcome the limitations, optical systems offer a good choice with the advantages of non-contact and distributed sensing. The established tracking technique, template matching or digital image correlation (DIC) has the limitation for tracking cables since selecting a rectangular region of interest for tracking might include the cable components as well as some background pixels (e.g. clouds or trees) which have inconsistent motion with the true cable motion. In this study, a motion estimation method based on cable edge detection was proposed and validated in field tests of two cable-stayed footbridges in Exeter, UK. A consumer-grade camera (GoPro) was adopted to record the videos of bridges and analysis results show that the method can measure the natural frequencies of cables accurately.

1 INTRODUCTION

1.1 Significance of cables in cable-stayed bridges

Cables are important components in cable-stayed bridges. Stay cables transmit the major loads acting on the girder to the pylon, directly support structural weight and traffic/human loading, and control the entire internal force distribution of the deck system. Thus the cable tension is a crucial factor in determining the overall condition assessment of a cable-stayed bridge structure.

1.2 Sensing technologies for cable tension measurement

Direct methods for cable force measurement e.g. hydraulic jacks and load cells are less appealing (Cho, Lynch, Lee, & Yun, 2009) due to the high cost, complicated installation and deterioration with time. Instead, the vibration method by which the cable force is estimated from natural frequencies using a pre-determined formula (Zui, Shinke, & Namita, 1996) or finite element approach, is often used due to simplicity, rapidness and economic feature. Accelerometers are generally mounted on cable surface for vibration measurement and natural frequency identification and currently wireless accelerometers (Cho et al., 2009; Yu et al., 2014) are available to reduce the installation efforts of extensive wires. However, direct access to structure for installation is still required.

Non-contact vision-based systems offer an alternative for cable vibration measurement owing the advantages e.g. quick and easy installation and features of distributed sensing (single camera for multiple point measurement simultaneously).

1.3 Review of vision-based methods for cable vibration measurement

Efforts have been involved in developing practical and efficient cable tracking methods. Conventional template matching based on correlation between two subset frames has been validated to be feasible through lab tests (Ye, Dong, & Liu, 2016) and field tests (S.-W. Kim & Kim, 2013) (S. W. Kim, Jeon, Kim, & Park, 2013) (Feng et al., 2016) while a major concern is that pixels within a selected template (a rectangular subset from a reference frame) might cover structural components as well as some background (e.g. clouds and tree branches) with inconsistent motions. Gradient-based optical flow estimation has been validated in short-span footbridges (Ji & Chang, 2008a) (Caetano, Silva, & Bateira, 2011) and a long-span cable-stayed bridge (Caetano et al., 2011) while this method is sensitive to changing lightning conditions. Edge detection according to the line-shape feature of cables (Ji & Chang, 2008b) was proposed for cable tracking and the difficulty of finding edge point correspondences was resolved by an assumption that the distance from one edge point to a fixed cable end keeps in a constant proportion to the whole cable length after deformation. This assumption sets the constraint on the field of view that should cover the full range of a cable including one cable end.

A particular difficulty of cable vibration measurement using vision-based system is provision of scaling for an accurate transformation from image motions to structure motions. Scaling factor derived from camera-to-cable distance (Ye et al., 2016) or one dimension correspondence (Chen, Wu, Tseng, Chen, & Lai, 2015) is popular due to the simplicity, and this method is expanded to consider the projection distortion (Ji & Chang, 2008a) given the cable vibration direction in image. Stereo vision has been used to extract the three dimensional displacement of cables (Ji & Chang, 2008b) given the physical location information of some control points.

When precise spatial measurements are not necessary, it is feasible to extract the natural frequency information directly from image motions (Chen et al., 2015). The prerequisite is that the cable motion is much smaller than the camera-to-cable distance, making it proper to use an affine camera projection model.

1.4 Purpose of this study

Although there have been several research studies on 'smart' vision-based systems for cable vibration measurement, the hardware used is always professional high-resolution cameras with long focal lens. To ensure good tracking performance, cables are required to occupy several pixels along the cable width direction in the image, which sets constraints on the camera-to-cable distance or the focal length of lens used.

The purpose of this study is to propose a cheap and portable system for cable vibration measurement over a short range (e.g. 30 metres). This system uses consumer-grade cameras (such as the currently popular GoPro), requires no access to structure and enables easy and quick equipment installation/removal. To that end, Section 2 provides system description including video processing methods. Section 3 validates the proposed system in two cable-stayed footbridges.

2 OPEN-SOURCE VISION-BASED SYSTEM

Applying a vision-based system for cable vibration measurement requires setting up one or more cameras in a stable location looking at the 'cable' of interest and deriving cable motions through video processing techniques. The hardware comprises one GoPro camera and a tripod shown in Figure 1. The recorded video files are post-processed in a custom-developed video-processing package.

Since the study purpose is to determine the natural frequencies of cable vibration instead of precise displacement values, the video processing is targeted at cable motion estimation in image without considering scale transformation between image and structural motions. The applications should satisfy that the cable motion is much smaller than the camera-to-cable distance, making it proper to use an affine camera projection model.

The video processing mainly includes two steps, edge detection and motion estimation. Edge detection is aimed at determining the cable direction in a small subset window while the cable motion is estimated from the distance between two extracted edges.

In edge detection step, a region of interest (ROI) including a small cable segment is selected for tracking. The image coordinates of edge point candidates are extracted in pixel-level resolution using Sobel operator and then refined to subpixel resolution using Zernike moment operator (Ghosal & Mehrotra, 1993) (Ying-Dong, Cheng-Song, San-Ben, & Jin-Quan, 2005). Outliers of edge point candidates are then removed using Hough line transform and the cable direction is then determined by line fitting among the inliers.

For motion estimation, an arbitrary direction (e.g. normal to an identified edge) was assumed as the cable motion direction. The cable motion is predicted from the distance between two edge lines along the assumed motion direction, which inherently has subpixel resolution. Even if the assumed motion direction is deviated from the true one, the motion estimate is proportional to the true motion, making no influence on the identification of cable natural frequencies.

Figure 1 Hardware for vision-based system

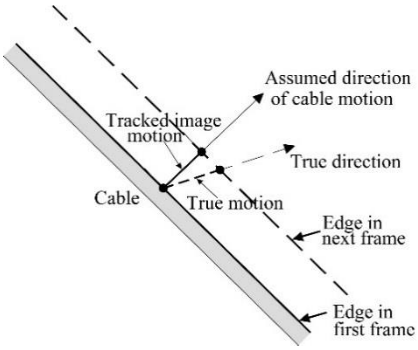

Figure 2 Cable motion estimated from edge shift

3 APPLICATIONS IN CABLE-STAYED FOOTBRIDGES

In this section, the proposed vision-based system was validated in two bridge applications for cable vibration measurement.

3.1 Miller's Crossing Bridge

Miller's Crossing Bridge is a cable-stayed footbridge in Exeter, UK as shown in Figure 3. One of the shorter cables is known to vibrate due to pedestrian traffic, so pedestrian excitation (jumping at the 2.4 Hz vertical natural frequency) was used to obtain the dynamic parameters of the cable.

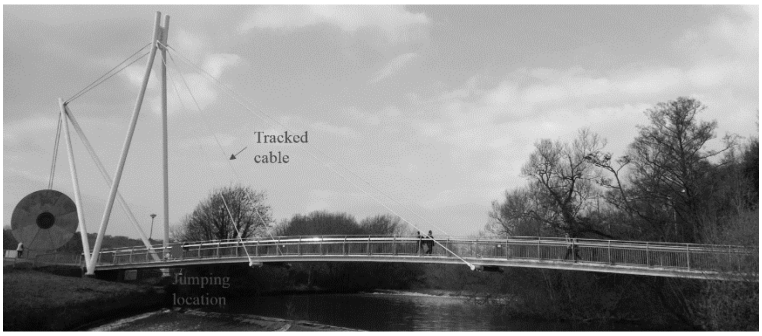

Figure 3 Miller's Crossing Bridge

A GoPro Hero4 Session video camera was mounted on a tripod approx. 30 m away from the bridge and the recorded video files were post-processed using custom-developed code. A sample frame is shown in Figure 4(a). The image includes salient distortion due to the setting of wide angle lens, thus the lens distortion was corrected ahead of cable tracking using offline camera calibration method (Chang & Ji, 2007) and the corrected image is shown in Figure 4(b).

(a) (b)

Figure 4 Captured frame from GoPro video: (a) raw image; and (b) image after distortion correction.

The results of cable motions are shown in Figure 5. In time histories of cable vibration, the maximum motion in the image is estimated to be 0.583 pixel. The corresponding power spectrum density is presented in Figure 5(c) identifying peak frequencies at 2.53 Hz, 5.03 Hz and 7.6 Hz. These values could be used to estimate cable tension once providing the cable length and mass properties.

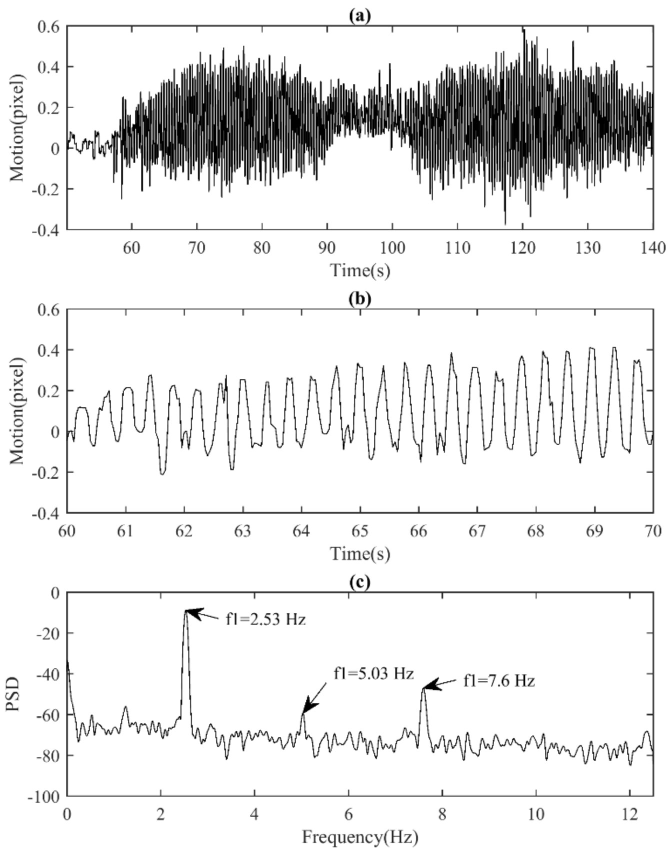

Figure 5 Tracking results of cable motion: (a) cable motion in time history, (b) Zoom-in view of cable motion, and (c) power spectral density of cable motion.

3.2 Baker Bridge

Baker Bridge is a 109 m cable-stayed footbridge in Exeter crossing the A379 dual-carriageway (See Figure 6). The bridge provides pedestrian access to the Sandy Park Stadium, the home ground of Exeter Chiefs Rugby Club and thus experiences heavy pedestrian traffic on match days.

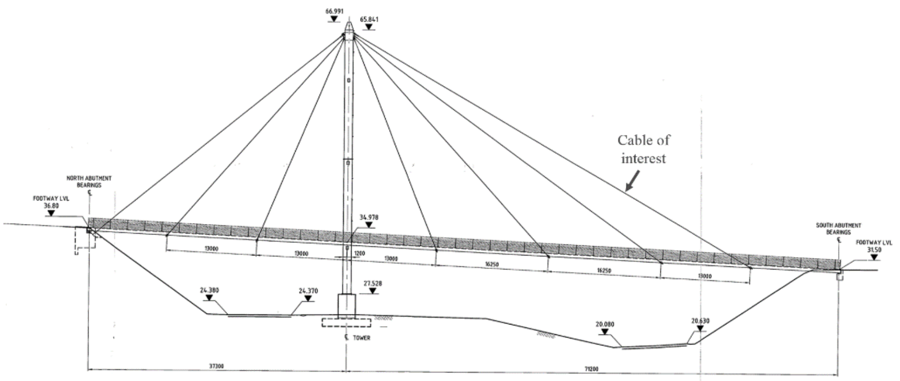

Figure 6 Elevation of Baker Bridge

A GoPro Hero 4 Black video camera mounted on a tripod was set up at the central reservation of the A379 dual-carriageway on a match day and Figure 7 gives sample frames at silent and fully occupied period of bridge.

(a) (b)

Figure 7 Two frames captured from recorded video files: (a) quiet period; and (b) fully occupied period.

The time history results of cable motions are shown in Figure 8 (a) and (b). The corresponding power spectral density shown in (c) indicates a clear peak at 1.67 Hz while peaks found at approximately twice and three times natural frequency are not sharp. This might be caused by the shift of cable natural frequency under heavy pedestrian loads, leading to the violation of the stationary process assumption in the Fourier transform analysis.

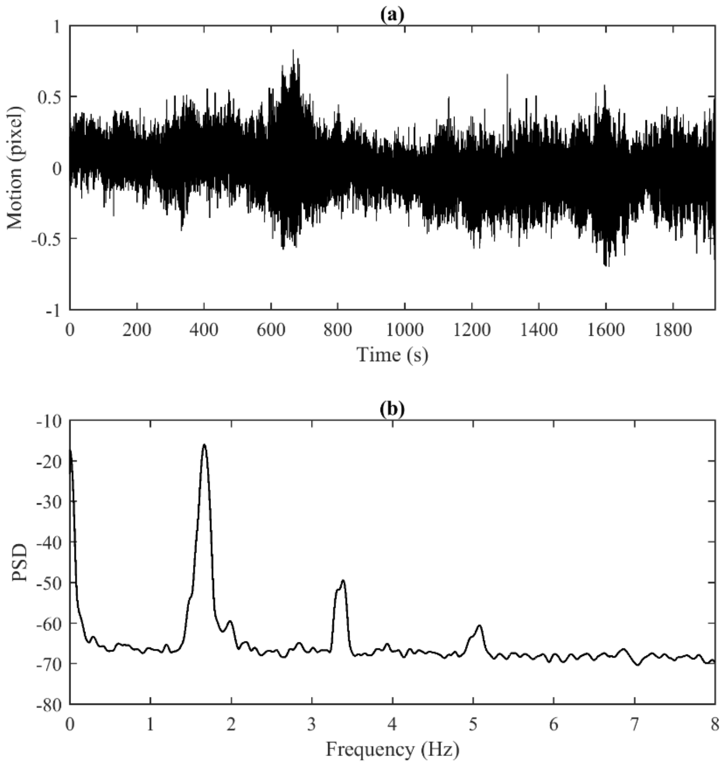

Figure 8 Tracking results of cable motion: (a) cable motion in time history; and (b) power spectral density of cable motion.

Continuous wavelet transform (CWT) was used to identify the instantaneous modal parameters of the bridge and the results are indicated in Figure 9. It is observed that the cable natural frequency was shifted from 1.66 Hz to 1.71 Hz when the bridge became fully occupied and shifted back when the bridge was empty again.

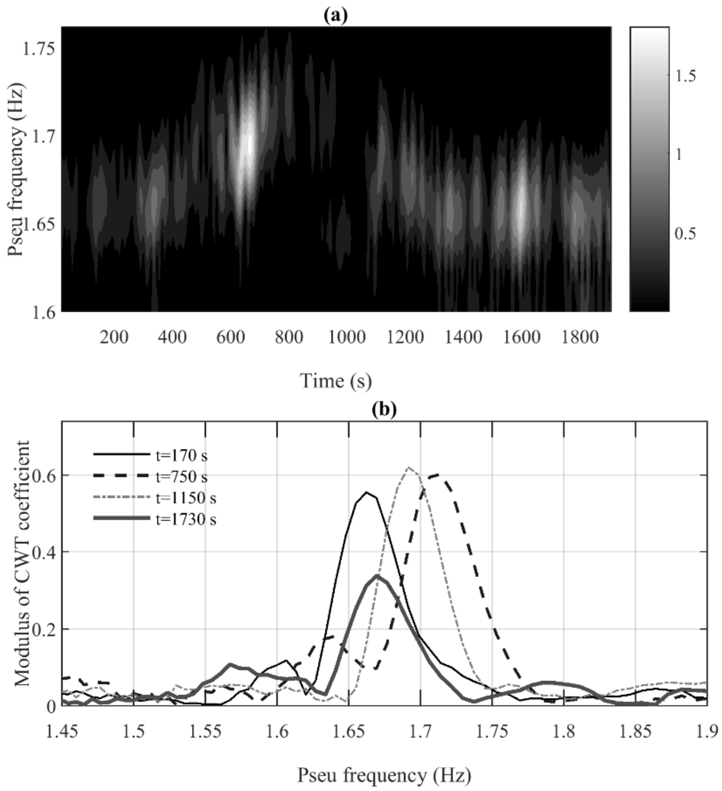

Figure 9 CWT results of cable motion: (a) contour plot of the time-frequency distribution of CWT coefficient modulus; and (b) instantaneous frequency contents at specified time step.

4 CONCLUSION

This study demonstrates the feasibility of consumer-grade cameras for non-contact cable vibration monitoring in bridges. The extracted information from cable monitoring could be employed for cable force estimation and performance assessment. The system also has the potential to monitor other slender line-shape structural components e.g. transmission towers.

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