Chapter 14
Design and Demonstration of an Improved Optical Multiplexer for Vision-based Vibration Monitoring of Civil Structures

Matthew Whelan, Youngjin Park, and Timothy Kernicky

Abstract Computer vision-based approaches to measuring the static displacement and vibration of civil structures offer the potential to reduce the cost and logistical complexity of structural health monitoring systems. However, the application of computer vision for displacement measurement of many civil structures is challenged by the small magnitude of displacements under operational loads relative to the physical size of the structure. Consequently, achieving sufficient measurement resolution of displacement with conventional vision-based systems typically requires imaging of a small field of view rather than the full expanse of the structure. As an alternative to costly synchronization of multiple cameras or the use of reference-based methods, an optical multiplexer can be used to acquire multiple sub-fields of view with a single camera to simultaneously acquire displacement measurements at several locations across a large civil structure. The authors have previously presented a low-cost liquid crystal optical multiplexer assembly with 3D printed fixture and demonstrated the ability of the multiplexer to track the displacement of optical targets within sub-fields of view. However, the opening and closing time of the general-purpose liquid crystal shutter limited the utility of the optical multiplexer for vibration measurement. This paper further explores the use of optical multiplexing for measurement of dynamic displacements by redesigning the instrumentation with a fast optical shutter. The design and operation of the optical multiplexer is presented including the selection and characterization of the optical shutter and imaged sub-fields of view. Additionally, translation of the technology from the laboratory to the field is examined by acquiring vision-based measurements from a structure under ambient conditions.

Keywords Optical multiplexing · Vision-based measurement · Vibration measurement · Full-field displacement measurement · Structural health monitoring

Introduction

Vision-based methods for structural health monitoring of civil structures have received significant attention over the past decade, driven by the potential to provide a convenient and relatively low-cost, non-contact approach to monitoring structural response. Significant improvements in image resolution of digital cameras have enabled accurate static and dynamic displacement measurements with consumer-grade cameras [1, 2]. Recent studies have demonstrated the capability of vision-based approaches to acquire structural responses and estimate system properties for structural health monitoring of full-scale bridges or critical bridge components. For example, an influence line for the vertical displacement at a midspan location of a continuous box-girder highway bridge has been constructed with a vision-based system [3], modal parameters of stay cables of full-scale bridges have been estimated using phase-based motion magnification to enable inverse identification of tension forces [4], and natural frequencies and damping ratios for several modes of a large cable-stayed bridge have been estimated using an array of consumer-grade cameras equipped with long focal lenses [5].

The motivation for introducing an optical multiplexer into a vision-based approach for monitoring civil structures stems from the inherent trade-off between field of view and spatial resolution. Wide field imaging is desirable to permit capture of

---

Matthew Whelan · Youngjin Park · Timothy Kernicky
Energy Production and Infrastructure Center
e-mail: mwhelan3@charlotte.edu; Y.Park@charlotte.edu; tkernick@charlotte.edu

Matthew Whelan · Timothy Kernicky
Department of Civil and Environmental Engineering, University of North Carolina at Charlotte, Charlotte, NC 28223
e-mail: mwhelan3@charlotte.edu; tkernick@charlotte.edu

Matthew Whelan et al. (eds.), *Dynamics of Civil Structures, Vol. 2*, Conference Proceedings
of the Society for Experimental Mechanics Series, https://doi.org/10.13052/97887-438-0147-4_14

as much of a structure into the image to maximize the sampled region. However, the spatial resolution is degraded by the use of a large field of view, since the pixel area of the imaging sensor is applied over a large physical area. The use of long focal length lenses, and subsequent reduction of the field of view to a small region of interest, is often necessary to produce sufficient spatial resolution to measure dynamic displacement of bridges [6]. In the absence of optical multiplexing, multiple cameras are required to acquire vision-based measurements at several regions of interest across a large civil structure. Alternatively, a roving camera technique developed by Wang et al. [7] can be employed where a series of targets or regions of interest are sequentially sampled while acquiring simultaneous images of a reference target with a second, stationary camera. However, this approach requires linear, time-invariant response, either controlled and repeatable or white-noise excitation, and independent compensation of camera motion for each camera. Optical multiplexing offers the potential capability to acquire multiple sub-fields of view using a single, stationary camera, thereby reducing the number of cameras and eliminating the challenges associated with roving techniques.

The current work builds on the design and demonstration of a low-cost optical multiplexer constructed with liquid crystal (LC) shutters and a 3D printed fixture that was previously presented by Whelan and Park [8]. The optical multiplexer uses the technique developed by Treeaporn et al. [9] that enables the superposition of multiple sub-fields of view onto a single imaging sensor, while providing a means to reconstruct the images of the individual sub-fields of view. The superposition of multiple sub-fields of view is achieved using a multiple beamsplitter arrangement, depicted graphically in Figure 1a. A beamsplitter reflects light while simultaneously transmitting light. This allows for the transmission of light reflected by any beamsplitters or mirrors positioned behind a beamsplitter, effectively superimposing multiple fields of view onto the common image sensor of the camera. By adjusting the orientation of the mirror and beamsplitters, the individual fields of view reflected to the camera can be controlled. To enable disambiguation of the composite image to facilitate reconstruction of the images of the individual sub-fields of view, the multiplexer uses LC shutters to acquire a sequence of three non-redundant measurements. This process is illustrated graphically in Figure 1b. First, an image is acquired with all shutters open, resulting in a composite image formed by all sub-fields of view. Subsequently, images are acquired with shutters sequentially closed, starting with the shutter in the first beamsplitter ahead of the mirror. If the shutters completely block all transmitted light, then the individual pixels intensities of the acquired composite images are the simple sum of the sub-image intensities and any measurement noise, which allows for direct inverse determination of the images of the individual sub-fields of view. However, LC shutters are imperfect shutters and do transmit a small fraction of light in the closed state, particularly if the orientation of the shutter is not perpendicular to the orientation of the camera lens. Treeaporn et al. [9] detail a procedure for estimating leakage coefficients experimentally to construct a system model capable of accounting for beamsplitter transmission and reflection coefficients as well as any absorptive losses.

Improvements to Optical Multiplexer Design

The low-cost optical multiplexer design presented in Whelan and Park [8] used two very low-cost 36 mm x 36 mm LC light valves to serve as both shutters and beamsplitters in the multiplexer. Although the design produced a working prototype that demonstrated the successful acquisition of static and dynamic displacement measurements from three sub-fields of view, the LC light valves imposed several practical limitations on the performance. First, the 38 mm x 38 mm size of the light valves was too small relative to the camera lens to acquire images from multiple fields of view with minimal overlap without obstruction by the optical mounts. Second, the low-cost LC light valves had relatively long opening and closing times, thereby limiting the practical switching speeds that could be used. At even a modest frame rate of 50 fps, a noticeable reduction in transmitted light was observed for the fields of view behind the front shutter. The reduction in transmitted light affected the ability to reconstruct the images for these fields of view at this frame rate, thereby limiting the ability of the original multiplexer design to be used for dynamic displacement measurement.

To improve the optical multiplexer design, the low-cost LC light valves were replaced with fast optical shutters in a larger format. Specifically, the 2nd generation fast optical shutter (FOS(G2)-IQ) manufactured by LC-Tec Displays AB with a 45.6 mm x 47.6 mm clear aperture area was selected for the improved multiplexer design. The model selected includes optical quality cover glass laminated to both sides of the shutter, which is recommended for imaging applications. These fast optical shutters feature a specified minimum open state transmittance of 38.5%, minimum contrast of 2000:1, maximum closing time of 1.8 ms, and maximum opening time of 6 ms when driven with a 4 V_{RMS} signal. In theory, the opening time of the fast optical shutter should permit the use of frame rates up to 150 fps without significant attenuation of the transmitted light, provided that the ambient light is sufficiently high enough to limit exposure times to around 1 ms or less. This frame rate was deemed sufficiently high for most envisioned civil structure applications of the optical multiplexer, as it results in a maximum effective sampling rate of 50 fps for each sub-field of view. For other applications requiring higher frame rates, one could use extra fast optical shutters, also available from LC-Tec Displays AB.

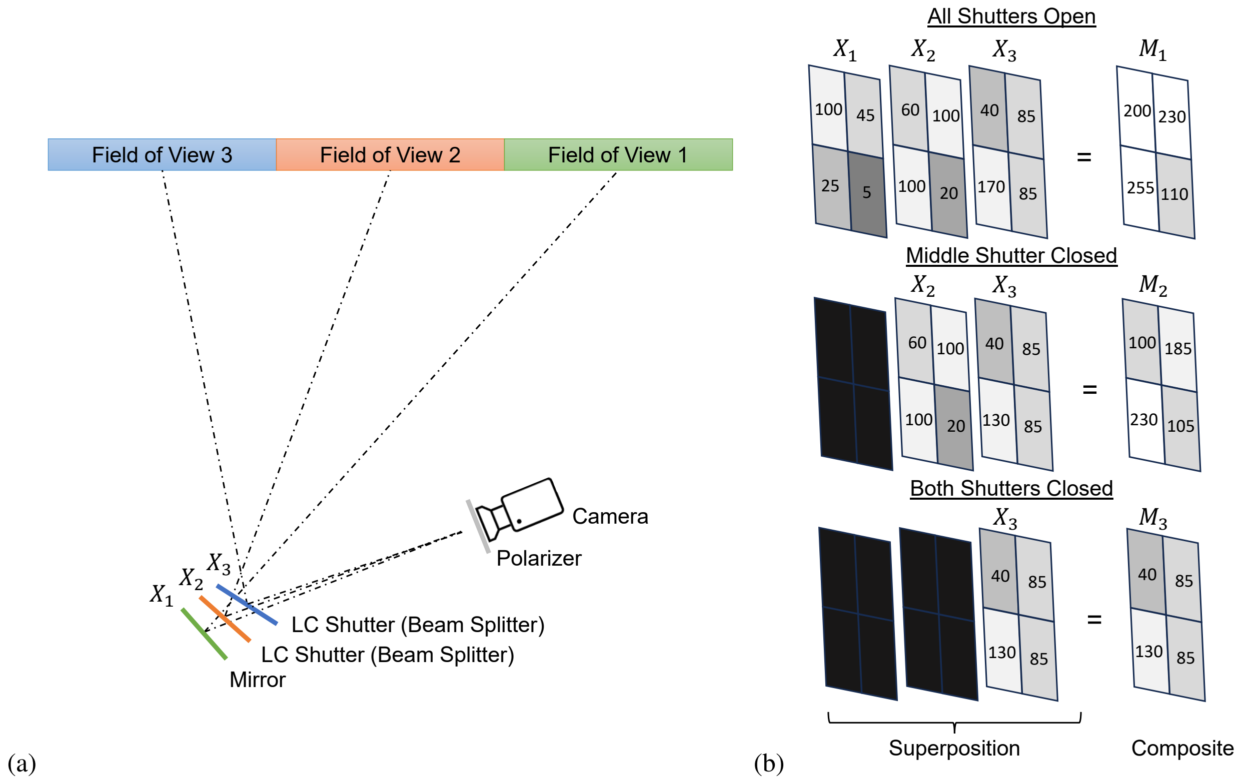

Fig. 1 Optical multiplexer: (**a**) design; (**b**) conceptual operation

The LC shutters in the optical multiplexer in Whelan and Park [8] were driven directly by 5V counter outputs from a National Instruments multifunction I/O device. However, driving an LC shutter directly from a 5V counter is not advisable due to the introduction of a DC bias that can degrade the performance of the shutter. Furthermore, the current rating of digital I/O channels is typically lower than the peak current required to achieve the specified switching speeds. To address both of these issues, a small driver circuit was developed to interface the fast optical shutters to the multifunction I/O device. The schematic for the circuit is shown in Figure 2a. The circuit relies on three synchronized counter output signals to establish the timing of the waveforms driving each shutter. One side of each shutter is driven by inverter gates connected to the first counter and wired in parallel to increase the potential to sink and source current. The other side of each shutter is driven by 2-input exclusive-OR gates, also wired in parallel. The inputs to the exclusive-OR gates are the signal driving the other leg of the shutter and additional counter signals that effectively control whether the shutter is driven closed or restored to the open position. Figure 2b depicts the waveforms from the counter signals and the resulting drive voltage across each shutter. Effectively, the Counter 0 signal establishes the polarity of the drive voltage across the shutters, while the Counter 1 and Counter 2 signals control whether a voltage potential is developed across each respective shutter to close the aperture. The SYNC signal is a simple digital output used as a start reference to synchronize the counters. This signal is also connected to the digital camera to synchronize the acquisition of frames. For the prototype developed for this work, a Texas Instruments SN74AC04N was used to provide the inverter gates and a Texas Instruments SN74AC86N was used to provide the 2-input exclusive-OR gates. Both integrated circuits are capable of providing ±24 mA current output at the supply voltage of 5V.

Lastly, the 3D printed fixture for the optical multiplexer prototype was redesigned to greatly improve the ease by which the arrangement of optical components can be established for a given experimental setup. Figure 3 presents renderings of the 3D printed fixture design in both an assembled view and an exploded view. The design of the slotted fixture that holds the optic mounts, while permitting for adjustment of the position and orientation of the mirror and LC shutters, is largely unchanged from the original design, except for increased sizing to accommodate the larger mirror and shutters. However, a horizontal guide and longitudinal guide were designed and fabricated to allow for the fixture to be secured directly to the camera rather than being independently supported. The adjustments permitted by the guides significantly reduce the time required to establish the positions and orientations of the optics to sample the desired sub-fields of view with the multiplexer.

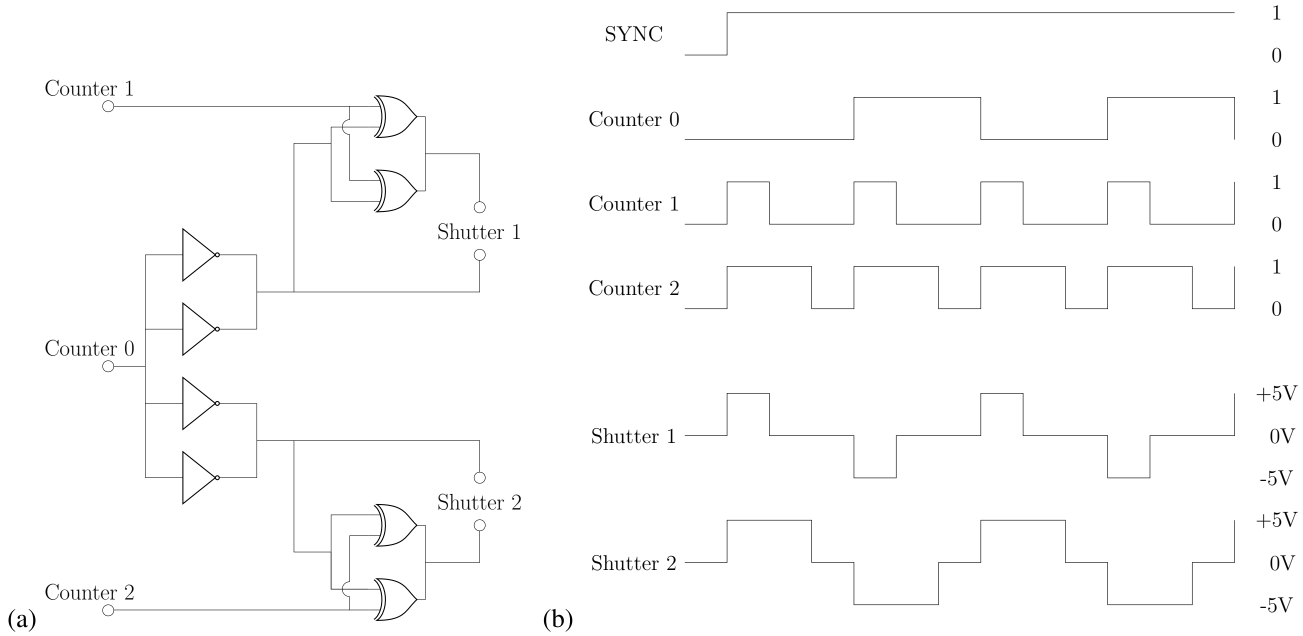

Fig. 2 Driving LC shutters with counter outputs: (**a**) schematic; (**b**) waveforms

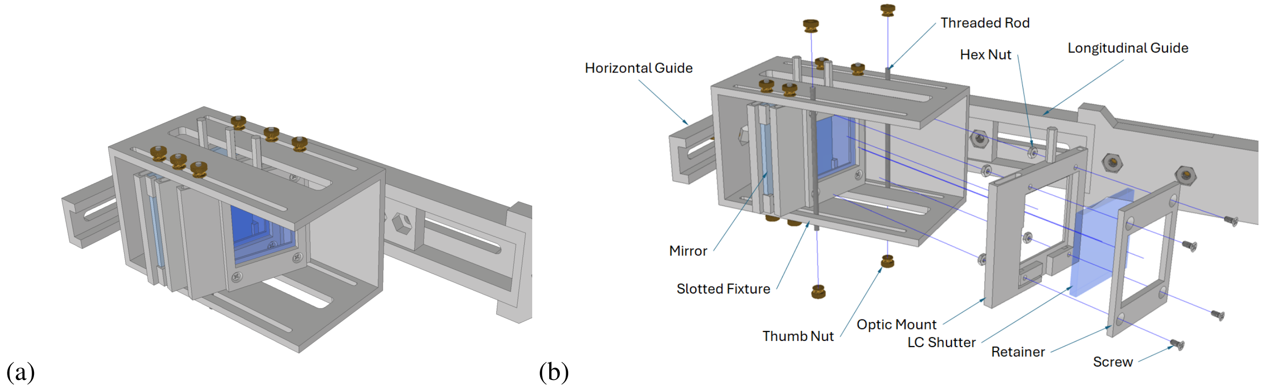

Fig. 3 Rendering of redesigned 3D printed fixture for optical multiplexer prototype: (**a**) assembled view; (**b**) exploded view

Field Demonstration

A preliminary field experiment was conducted with the new optical multiplexer prototype to demonstrate its performance in monitoring the dynamic response of a geometrically large structure under ambient conditions. Specifically, a light pole for the football stadium on the University of North Carolina at Charlotte campus served as the structure of interest for this demonstration. Figure 4a presents a photograph of the stadium light pole taken at the time of the testing. A Phantom VEO 640L high-speed color camera was used to acquire the images with a frame rate of 150 fps and 4 Megapixel resolution. A Nikon AF Micro-Nikkor 200mm f/4D IF-ED lens was used with the camera to focus the sub-fields of view on three local regions of the pole: one near the groundline, one around the midheight of the pole, and one containing the supported lights at the top of the pole. Figure 4b provides a photograph of the optical multiplexer configured directly below the long focal length lens attached to the high-speed camera. The multiplexer was supported secondarily by a small tripod to mitigate vibration of the fixture.

A series of composite images obtained from one of the recordings is presented in Figure 5. It is critical to note that a linear polarizing filter of appropriate size was not available for the lens of the camera at the time of the testing and could not be sourced before the submission deadline. Consequently, the image reflected from the front-most LC shutter during the test was comprised of non-collimated light, while the images reflected from the mirror and middle LC shutter were

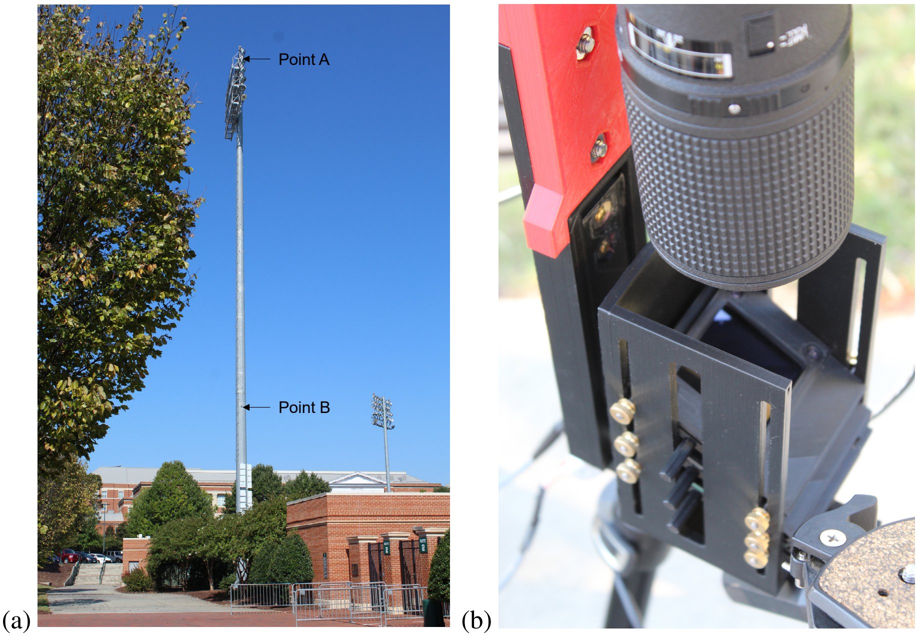

Fig. 4 Photographs of field demonstration: **b**) stadium light pole; (**b**) tripod-mounted camera with optical multiplexer

linearly polarized by their transmission through the open LC shutters. As a result, the intensity of light from the sub-field of view reflected by the front-most LC shutter, X_3, was significantly higher than that produced by the other sub-fields of view. This imbalance caused the X_1 and X_2 images to be less apparent in the composite images and degraded the quality of the reconstruction of the individual sub-fields of view. Consequently, reconstructed images of the individual sub-fields of view are not presented in this paper and will be reserved for future publications after the authors repeat the experiment with a linear polarizing filter to improve the relative balance of the sub-field of view image intensities. This future work will be presented at the conference and will serve to formulate conclusions and recommendations related to the performance of the revised optical multiplexer design.

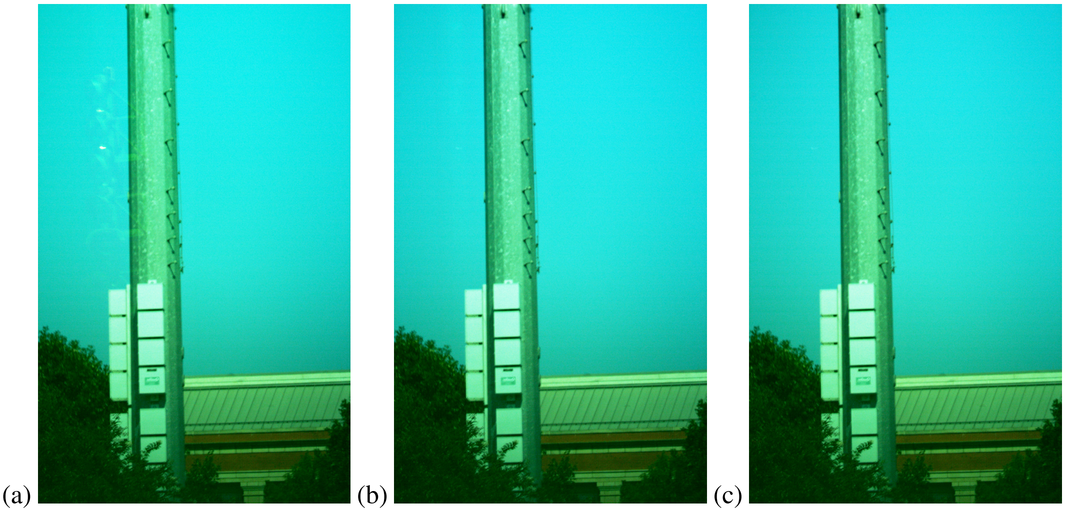

Fig. 5 Composite images obtained with prototype optical multiplexer: (**a**) all shutters open: $X_1 + X_2 + X_3$; (**b**) middle shutter closed: $X_2 + X_3$+leakage; (**c**) both shutters closed: X_3+leakage

Despite the issue related to the relative intensities of the sub-fields of view that arose due to the lack of a polarizing filter, the images recorded with the optical multiplexer assembly were post-processed to extract displacement time history estimates to demonstrate the ability to track features from different sub-fields of view. The Sandia National Laboratories

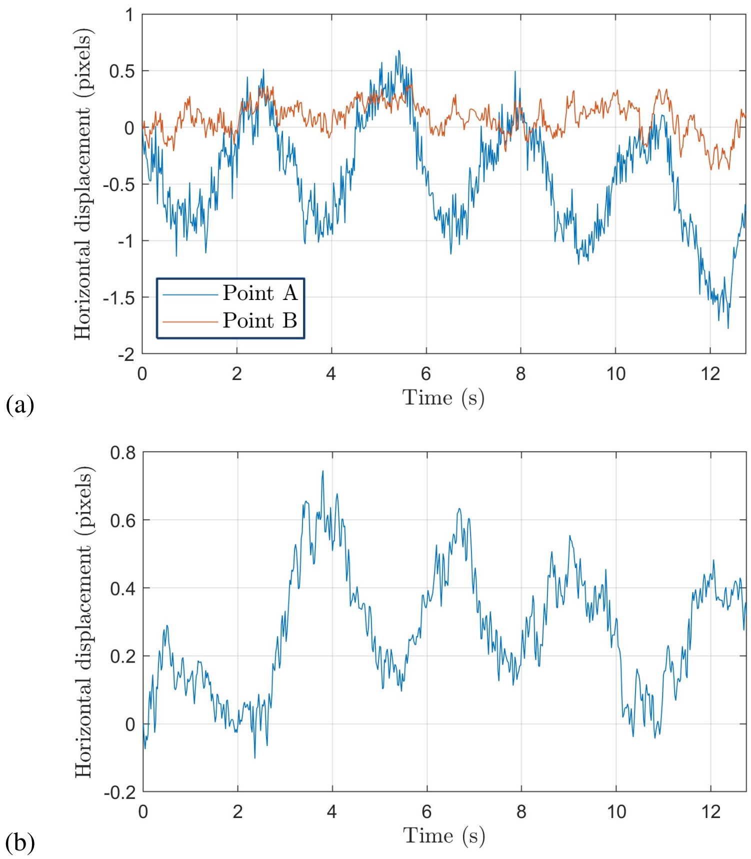

Fig. 6 Displacement time histories obtained from tracking of natural features: (**a**) with optical multiplexer ; (**b**) without multiplexer

Digital Image Correlation Engine (DICe) software application [10] was used to extract displacement time histories from regions with natural features using the tracking analysis mode. For all analyses, the gradient-based optimization method was used after Gauss filtering the images with a 13 pixel filter window. The two locations, denoted as Point A and Point B in Figure 4a, which originate from two different sub-fields of view were tracked over the duration of one of the recordings. Point A originates from the sub-image reflected from mirror, while Point B originates from the sub-image reflected by the front-most LC shutter. During the testing, the weather was mild and the wind speed was estimated to be only around 8 km/hr (5 mph) based on observations from a local weather station. As a result of the limited ambient excitation, the vibration amplitude in the light pole was expected to be low. Figure 6a provides the time histories obtained from tracking natural features of the pole at the locations of interest. The displacements amplitudes are generally less than a pixel in amplitude, but the relative amplitudes at the two locations suggest vibration of the light pole in its fundamental mode. By Fourier transform, the fundamental natural frequency of the pole was estimated to be 0.39 Hz. For comparison, the multiplexer was removed from the camera and the top region of the pole was monitored using a conventional configuration of the high-speed camera with the same long focal length lens. A horizontal displacement time history obtained by trajectory tracking of Point B without the multiplexer is presented in Figure 6b. Since this motion was captured at a different instance in time than the data in the corresponding Figure 6a, the waveforms are not expected to be identical in either amplitude or phase. However, the dominant period of the response is very similar to that observed with the optical multiplexer and Fourier transformation of the data confirmed that the frequency component of greatest amplitude occurred at 0.39 Hz.

Conclusion

Optical multiplexing has been previously shown to provide a practical means of sampling multiple regions of interest across geometrically large civil structures while maintaining the improved spatial resolution obtained with the use of long focal length lenses. This paper discloses improvements to a preliminary low-cost optical multiplexer design to improve the capabilities for monitoring dynamic displacements. Specifically, the general purpose LC light valves were replaced with large format LC fast optical shutters to significantly reduce the opening and closing times to enable faster frame rates to be used without attenuating the intensity of light from the sub-fields of view transmitted through the LC shutters. A circuit for efficiently driving the LC shutters without introducing DC bias was presented and modifications to the 3D printed fixture to improve the usability of the optical multiplexer assembly were described. A preliminary field experiment was conducted where the vibration of a stadium light pole was monitored with high-speed camera equipped with a long focal length lens and the prototype optical multiplexer assembly. The images acquired during the testing confirm proper functionality of the LC shutters at a frame rate of 150 fps and enabled displacement measurements through feature tracking within different sub-fields of view. Due to the absence of a linear polarizing filter, a significant imbalance of light intensity across the images from the three sub-fields of view was present, which compromised the quality of reconstruction of the individual sub-fields of view. Remedy of this issue is straightforward and will be presented in conference presentation as well as future publications.

References

1. Khuc, T. and Catbas, F. “Completely contactless structural health monitoring of real-life structures using cameras and computer vision”. *Structural Control and Health Monitoring*, 24:1–17 (2017)
2. Xu, Y., Brownjohn, J., and Huseynov, F. “Accurate deformation monitoring on bridge structures using a cost-effective sensing system combined with a camera and accelerometers: Case study”. *Journal of Bridge Engineering*, 24 (2019)
3. Zhou, Y., Hu, J.N., Hao, G.W., Zhu, Z.R., and Zhang, J. “Identification of influence lines for highway bridges using bayesian parametric estimation based on computer vision measurements”. *Journal of Bridge Engineering*, 28(12) (2023)
4. Wangchuk, S., Siringoringo, D.M., and Fujino, Y. “Modal analysis and tension estimation of stay cables using noncontact vision-based motion magnification method”. *Structural Control and Health Monitoring*, 29(7):e2957 (2022)
5. Bocian, M., Nikitas, N., Kalybek, M., Kużawa, M., Hawryszków, P., Bień, J., Onysyk, J., and Biliszczuk, J. “Dynamic performance verification of the redziński bridge using portable camera-based vibration monitoring systems”. *Archives of Civil and Mechanical Engineering*, 23(40):1–19 (2023)
6. Xu, Y., Brownjohn, J., Hester, D., and Koo, K. “Dynamic displacement measurement of a long span bridge using vision-based system”. 8th European Workshop On Structural Health Monitoring (EWSHM 2016) (2016)
7. Wang, M., Ao, W.K., Bownjohn, J., and Xu, F. “Completely non-contact modal testing of full-scale bridge in challenging conditions using vision sensing systems”. *Engineering Structures*, 272:114994 (2022)
8. Whelan, M. and Park, Y. “Enhancing vision-based structural displacement measurement of civil structures through optical multiplexing”. *Dynamics of Civil Structures, Vol. 2*, Proceedings of the International Modal Analysis Conference XLII (2024)
9. Treeaporn, V., Ashok, A., and Neifeld, M.A. “Increased field of view through optical multiplexing”. *Optics Express*, 18(21):22432–22445 (2010)
10. Turner, D., Crozier, P., and Reu, P. “Digital image correlation engine”. Technical report, Sandia National Laboratories (SNL) (2015)