High-speed Vision System for Dynamic Structural Distributed Displacement Analysis

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Abstract. Structural health monitoring (SHM) has become a prominent topic in the field of civil engineering in detecting structural damage, estimating remaining service life of structure, optimizing decision making process on maintenance, and aiding performance-based structure design methodology. Dynamics measurement is one of important techniques to diagnose deterioration of structures by inspecting their dynamics properties, mainly derived from displacement time-series from multiple measurement points. Various conventional distributed displacement measurement techniques of civil structures currently in place have been limited due to various constraints: inadequate accuracy, overly-localized measurement point, measurement drift, robustness issue on field usage, structural obstruction, and reliability for long-term installation. Optical technique utilizing LED markers has been proposed as an alternative for dynamic distributed displacement measurement, providing visual cue and easily-identifiable marker position. The technique incorporates high-speed camera system and telephoto lens to capture both lateral and vertical displacement of bridge members, LED markers to cope with the insufficient incident light over long distance and small camera aperture, and computer vision system to calculate multiple markers’ displacement simultaneously. Further analysis was conducted to evaluate structure natural vibration frequencies using FFT (Fast Fourier Transform) peak-picking method.

1. Optical displacement measurement
Structures are subject to repetitive and temporary external forces from wind, current, quakes, and load in addition to its inherent weight. These forces may cause either small or large displacement of structure’s members. In the effort in detecting structural damage, estimate remaining service life of the structure, scheduling maintenance, and improving design methodology, structural health monitoring is widely employed on civil structures \cite{1}. Dynamics measurement is one of technique to diagnose deterioration of structures, mainly derived from distributed displacement measurement. Furthermore, evaluation on natural vibration frequencies of the structure may tell vibration characteristics.

Various distributed displacement measurement techniques currently in place have been limited due to several constraints: inadequate accuracy, precision, and both spatial and temporal resolution, measurement drift, ease of practical setup, and reliability for long-term installation. Vision measurement provides alternative for contact-less distributed displacement measurement over some distance. The increasing availability of high-performance vision-based systems provides the potential for developing adaptable/reconfigurable monitoring systems of complex deformation field measured at selectable locations and orientations \cite{2}.
Several implemented vision-based systems for displacement measurement were still limited. Target-less vision-based displacement sensor system was proposed by extracting and tracking feature points in video stream [3]. Multiple displacement point approach can be achieved using image key-points [4], but these methods largely depend on low noise image and crisp edges. Given that only feature point was extracted from a small area and edge detection is susceptible to focal blur, the system isn’t suitable for distributed measurement points with different frontal distances, long distance measurement, and low ambient lighting condition. Optical motion tracking system using surveillance camera was proposed to measure induced motion in the event of an earthquake [5], but the system is limited due to low frame rate, and low pixel resolution of the surveillance camera, and in the event of an actual earthquake, inherent camera self-vibration resulting in no steady measurement reference point.

A more complex system incorporating two cameras equipped with telephoto lens and non-coplanar control points markers with Affine camera modelling has been proposed to measure tri-axis displacement and rotation of fixed monitoring zone of a structure [6]. Considering the extended period of operation, the geometry of components may change due to temperature effects and camera frame synchronization had yet been taken into account.

Optical system with telephoto lens, focal length extender, and active lighting device close to the camera may develop noticeable inaccuracy due to camera head vibration and heat wave from the lighting device, thus operating time of the lighting device needs to be limited [7]. This renders such system only suitable for structures with routine periodical loading condition such as railway bridge.

The contribution of this work is to capture lateral and vertical displacements of high-contrast markers installed on a structure with different distances and estimating natural vibration frequencies of the structure.

2. Truss vibration experiment with arbitrary forcing action

2.1. Experiment structure

Bridge model used for the experiment is Warren truss structure with L-beam aluminum (25 mm flanges, 1.2 mm thickness) for end posts, top and bottom chords, and flat aluminum strips (15 mm width, 2 mm thickness) for the struts and diagonal members. The bridge model incorporates no deck and bracing. The span, height, and width of the truss are 4 m, 21 cm, and 33 cm respectively. LED markers are 5 mm with white color, installed with 25 cm distance between one another. Figure 1 shows 16 LED makers installed on a single side of lower chord of the truss. Excitation force was applied to the center of the span on both bottom chords with arbitrary direction.

Figure 1. Truss structure with LEDs attached on a single lower chord of the truss.
2.2. Vision system settings

Focal length, aperture, and focus distance need to be adjusted proportionally to cover the whole span of the truss within the depth of field of the camera. The equation to the depth of field is given as:

\[ D_p = D_f - \frac{\epsilon ND_f^2}{f^2 + \epsilon ND_f}, \quad D_d = D_f + \frac{\epsilon ND_f^2}{f^2 - \epsilon ND_f} \]

(1)

where \( D_p \), \( D_d \), and \( D_f \) are depth of field near distance, far distance, and focus distance respectively. \( N \) is aperture number, \( f \) is focal length, and \( \epsilon \) is blur diameter. Optical settings were 9.3 m focus distance with F/32 aperture at 410 mm focal length which resulted in depth of field of 4.178 m with 22 px acceptable blur diameter, covering the whole span of the truss.

Camera head was set to capture vibration of the truss at 180 fps with 10 seconds duration. Summary of vision system specification is shown in Table 1. Figure 2 shows general overview of the experiment setup.

| Camera        | Lens                          | Computer         |
|---------------|-------------------------------|------------------|
| Ximea MQ042MG-C | SIGMA APO HSM 300-800         | Dell Latitude 3540 |
| Resolution    | 2048x1024 px                  | Memory 8 GB      |
| Sensor        | 5.5 \( \mu \)m pitch         | Focus distance 9.3 m |
| Exposure, frame rate | 5 ms, 180 fps          | Aperture F/32     |
|               |                               | CV library OpenCV 2.4.8 |

2.3. Scaling factor

Scaling/calibration factor gives estimate between vision-system resolution in pixels and actual physical dimension. For setups with non-perpendicular lens optical axis between camera and markers, scaling factors for lateral and vertical direction need to be estimated separately [8]. Calibration was done taking into account sensor size and distance between camera and marker.

To eliminate occlusion between markers, the camera system was placed slightly away from the truss axis both in lateral and vertical directions, resulting in a slanted angle between markers and the optical axis of the camera, thus scaling factor will be compensated following the equation:

\[ SF_v = \frac{11.27D_m}{f\cos(\pi - \tan(D_v/D_m))}, \quad SF_l = \frac{11.27D_m}{f\cos(\pi - \tan(D_l/D_m))} \]

(2)
Figure 3. Captured frames of sixteen markers showing minute displacements between $t=3$ s (a) to $t=5.5$ s (f) with 0.5 s interval between each other.

where $D_f$, $D_v$, $D_l$, and $D_m$ are frontal distance, vertical distance, lateral distance, and marker distance (Phytagorean resultant of $D_f$, $D_v$, and $D_l$). $SF_v$ and $SF_l$ are scaling factor in vertical and lateral direction respectively.

Camera head was put 45 cm higher than the chord on which all sixteen LED markers were installed with slanted lateral angle between camera optical axis and bridge axis, resulting in lateral distance of 20 cm between Marker1 and optical axis and 13.3 cm between Marker16 and optical axis. These frontal, lateral, and vertical distances between camera axis and LED markers were taken into account to calculate the appropriate scaling factor of each individual marker.

3. Captured marker movement and extracted displacement

Pixel-wise movement of each marker was translated to actual displacement using its respective scaling factors after subtracted from its steady-state value. Each marker’s centroid was extracted using OpenCV’s cvblob() blob detection function then multiplied to its respective scaling factor to obtain distributed displacements of the structure after firstly subtracted from its steady state value.

Figure 3 shows six frames capturing minute pixelwise movement of markers from $t=3$ s to $t=5.5$ s with 0.5 s interval. Figure 4 shows the truss’ chord displacement from the same time span. Figure 5 shows Marker9 displacement, positioned at the center of the truss’ span, over the course of 10 s capture duration and highlight between $t=3$ s to $t=4$ s.

4. Vibration natural frequency analysis

FFT analysis was conducted to evaluate natural frequencies of the structure vibration. Peak-picking method was applied to frequency response of Marker9 vibration to extract up to fifth mode of vibration. Only 1024 samples ($t=2.5$ s to $t=8.183$ s) was selected in order to avoid adding initial transient response to the natural frequency analysis. Figure 6 shows the structure’s frequency response both lateral and vertical directions. Table 2 summaries the natural vibration frequencies in both lateral and vertical directions.

Unique natural vibration frequency was found on 8.6133 Hz for lateral direction and 19.6875 Hz for vertical direction with the rest of the natural vibration frequencies are most likely due to material characteristics. The higher unique natural vibration frequency on vertical direction compared to one of lateral direction shows that the truss is more rigid vertically.
Figure 4. Chord displacement between $t = 3 \text{ s}$ to $t = 5.5 \text{ s}$.

Figure 5. Marker9 lateral displacement(a) and vertical displacement(b) for the whole ten seconds capture duration, also highlight between $t = 3 \text{ s}$ and $t = 4 \text{ s}$ for lateral displacement(c) and vertical displacement(d).
Figure 6. Normalized frequency response of the truss in lateral direction (a) and vertical direction (b).

Table 2. Natural vibration frequencies of the truss.

| Direction  | Natural frequencies (Hz) |
|------------|--------------------------|
|            | Mode 1 | Mode 2 | Mode 3 | Mode 4 | Mode 5 |
| Lateral    | 8.6133 | 15.2930 | 39.5508 | 41.8359 | 45.5273 |
| Vertical   | 15.2930 | 19.6875 | 39.5508 | 41.8359 | 45.5273 |

5. Conclusion

High-speed (180 fps) vision system, concurrently measuring the lateral and vertical displacement of multiple markers, has been proposed for structural dynamics analysis of truss structure. FFT peak-picking analysis was conducted to evaluate structure’s natural vibration frequencies.

Several improvements could be made to the experiment: calibration against external displacement sensors to verify measured displacement accuracy and precision, longer capture duration reaching steady state again after excitation to find for any residual plastic displacement and to obtain higher FFT resolution.

6. References

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