DIRECT MEASUREMENT OF DISPLACEMENTS IN VIBRATING STRUCTURES THROUGH VISION-BASED APPROACHES

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This paper reports the results of an analytical and experimental study to develop, calibrate, implement and evaluate the feasibility of a novel vision-based approach for obtaining direct measurements of the absolute displacement time history at selectable locations of dispersed civil infrastructure systems such as long-span bridges. The measurements were obtained using a highly accurate camera in conjunction with a laser tracking reference. Calibration of the vision system was conducted in the lab to establish performance envelopes and data processing algorithms to extract the needed information from the captured vision scene. Subsequently, the monitoring apparatus was installed in the vicinity of the Vincent Thomas Bridge in the metropolitan Los Angeles region. This allowed the deployment of the instrumentation system under realistic conditions so as to determine field implementation issues that need to be addressed. It is shown that the proposed approach has the potential of leading to an economical and robust system for obtaining direct, simultaneous, measurements at several locations of the displacement time histories of realistic infrastructure systems undergoing complex three-dimensional deformations.

INTRODUCTION

One of the main problems to be resolved, among the numerous practical issues in the field of structural health monitoring (SHM) to be overcome, is the accurate measurement of the time history of the three-dimensional deformations of complex structures, such as flexible bridges, at many locations and orientations, in order to define the evolving (time varying) nature of the structural deformation field of the bridge and its sub-components (such as cable stays, etc). The increasing availability of high-performance vision-based systems, at affordable cost, provides the potential for developing an adaptable/re-configurable monitoring systems that serve a dual purpose: enhanced surveillance capabilities and high-fidelity monitoring of complex deformation field measured at selectable locations and orientations.

Structural response information due to the effects of dynamic loads on dispersed civil infrastructure systems is vital to accurately evaluating the structural integrity of such systems. Conventional monitoring instruments such as accelerometers, linear variable-differential transformers (LVDTs), and global positioning systems (GPS) have various practical limitations in obtaining accurate data from the three-dimensional motions at many locations. However, vision-based methods have demonstrated promising results in both laboratory and field experiments. Vision-based approaches offer the potential of both high spatial and temporal resolution.

The goal of this study was to evaluate the feasibility and determine practical implementation issues related to the deployment of a vision-based sensor system for the direct measurement of displacement time histories of selected locations on a bridge undergoing ambient oscillations.

GPS-Based Monitoring Limitations

Another method that holds promise in structural monitoring is the Global Positioning System (GPS). This method has also been the focus of research, including the monitoring of structural deformation at Pacoima Dam, California, using continuous GPS as demonstrated by Behr et al., and Celebi et al. Roberts et al. performed a study to monitor the movement of the Humber Bridge, the third longest suspension bridge in the world. Hyzak et al., Teague et al., Celebi and Sandli all studied the effects of utilizing GPS for measuring displacement on structures.
However the use of GPS to track displacements of dispersed civil infrastructures such as bridges has some limitations. Most of the published studies of GPS have shown that it has an accuracy of about $\pm 1$ cm in the horizontal direction and $\pm 2$ cm in the vertical direction. The cost of high-accuracy, and high sampling rate GPS-based tracking is significantly more than vision-based approaches. In addition it has been shown in a field study by Wieser and Brunner (2002)\(^7\), that GPS is not practical for measuring bridge deck movement due to the multi-passing and diffraction effects associated with cables, which could result in several centimeters of variance. It is also known that multi-path issues are the major source of error in GPS, and significant research is being focused on this area. Another area of limitations in GPS capability that was studied in the context of bridges is the effects of atmospheric phenomena. Research in this area has shown that, if the residual tropospheric delay is not properly modeled, it could introduce several centimeters of positioning error. Atmospheric effects, such as ionospheric delay, are the main impact factors when single frequency GPS receivers are used. Also it was noted that the visibility and geometry of the satellite constellation during the observation periods has a negative influence on the quality of measurements.

OPTICAL INSTRUMENTATION SYSTEM ARCHITECTURE

A schematic diagram of the target bridge with the optical instrumentation mounted on it is shown in Figure 1. The general view shows the camera located at one of the bridge columns, while the optical target is located near the mid span of the bridge. The detailed view shows that the two targets were placed under the bridge deck, and were attached to some of the support trusses.

The high fidelity video camera had a resolution of 520 lines and a capability of 450 digital zoom. The targets consisted of high-resolution low-power light-emitting-diodes (LED). Each target consisted of two LED’s, spaced at a known distance, in order to calibrate the movement of the target. Both lights were lit for fifteen seconds at the beginning of the experiment, after which one light was left on for the remainder of the time.

PROCEDURE FOR OBTAINING ACCURATE DISPLACEMENT TIME HISTORIES FROM ACCELERATION MEASUREMENTS

In order to perform a reliable dynamic analysis of a structural system, the corresponding data must consist of accurate measurements. In most dynamic analysis the recordings of signals are primarily acceleration records, and therefore the velocity and displacement are obtained indirectly through integration of the corresponding acceleration records. The degree of accuracy of the integrated data depends on several factors such as the sampling rate, frequency content of the signal, the length of the record and the nature of the signal.

The most common method for obtaining velocities and displacements through integration of acceleration records involves filtering the low-frequency content from the data in order to reduce the effects of (usually) unimportant low-frequency components. However, this operation has to be done with care so as not to filter out significant low frequency components which become more important as the structure becomes larger and more dispersed. This is precisely the situation that is encountered in the monitoring of long-span flexible bridges.

In order to reduce the errors in the integration procedure due to the missing information concerning the initial conditions, the following procedure was utilized in the digital signal processing phase:

- Band-pass filter the acceleration record between 0.05 – 30 Hz.
- Integrate the acceleration once to obtain the velocity record.
- Repeat the band-pass filtering of the velocity record.
- Integrate the processed velocity record to obtain the displacement record.

An important requirement for accurate data processing is that the acceleration record duration be much longer than the longest characteristic period of interest. As can be seen from the above procedure, the main steps in the algorithm are a two-level sequence of band-pass filtering, integration, and de-trending. The validation of the method was performed on synthetic data of a finite element model, and on shake table measurements in the laboratory as well.
FIELD MEASUREMENTS FROM VINCENT THOMAS BRIDGE

The Vincent Thomas Bridge is located in San Pedro, California, and is a major transportation artery connecting Los Angeles with its harbor. It is a cable-suspension bridge, approximately 1850 m long, consisting of a main span of approximately 457 m, two suspended side spans of 154 m each, and a ten-span approach of approximately 545 m length on either end. The roadway accommodates four lanes of traffic. The bridge was completed in 1964, and in 1980 was instrumented with twenty-six accelerometers as part of a seismic upgrading project.

Currently, the sensor network is maintained by the State of California Department of Conservation (CDC) Office of Strong Motion Studies through California Strong Motion Instrumentation Program (CSMIP). Figure 2 shows the layout of the location of all 26 sensors mounted on the bridge. Notice that the eastern half of the bridge is more densely instrumented. This is because the analog recorder is housed in the eastern cable anchorage. Sixteen accelerometers are distributed at various locations and in lateral, longitudinal and vertical directions about the superstructure itself.

After the 1994 Northridge earthquake in the Los Angeles area, the VTB was deemed to be vulnerable to anticipated earthquakes, and was extensively retrofitted by the California Department of Transportation for earthquake resistance from 1997-2000. The structural characteristics of the bridge were enhanced by strengthening critical components and by installing 36 large passive viscous dampers to mitigate the relative motion under strong shaking of the bridge roadway with respect to its piers. Since the condition assessment of these essential dampers is crucial to the safe operation of the bridge, it is necessary to accurately measure the time history of the relative displacement across the terminals of the dampers.

Optical Instrumentation

The high resolution digital camera discussed above was mounted firmly at the center of the VTB west tower strut. Target frames were carefully designed in order to capture the motion of the target without influence from surrounding light noises. The targets consisted of black steel sheets 28 inches high by 32 inches wide, and two high-resolution red lights (LED) were mounted on these targets. Figure 3 shows the configuration of these targets.

Optical Data Reduction

Optical data was transferred digitally to a PC at a rate of 30 frames per second. In order to determine the motion of the bridge, a software program was developed to track the motion of each picture frame. The program consists of outlining the orbit of the red light and filtering the other colors with respect to red, in order to obtain the highest intensity of the red spot. The following details the data reduction algorithm.

The entire optically recorded data of 30 minutes was transferred to bitmap files by reading each frame into a separate file. Each bitmap file was converted into a matrix A_{ij}, where i and j represent the horizontal and vertical pixel intensity of the file. A color mask was then applied to filter all non-red components of the light intensity. The A_{ij}'s are integers having a value ranging from 0 - 255 representing the intensity of the resulting filtered intensity map. The area of interest, the center of the red spot for the first frame, was then identified by obtaining the highest value of A_{ij}'s, and a bounded matrix [B] was obtained, while ignoring the intensity

Figure 2. VTB sensor location.
terms of the surrounding sub-matrices [S]. The following equation represents the matrices selection:

\[
[A] = \begin{bmatrix}
[S_{11}] & [S_{12}] & [S_{13}]
\end{bmatrix}
\begin{bmatrix}
[S_{21}] & [B] & [S_{23}]
\end{bmatrix}
\begin{bmatrix}
[S_{31}] & [S_{32}] & [S_{33}]
\end{bmatrix}
\]

(1)

Since the camera used did not have a sufficiently high resolution, some of the recorded bitmap files contained what is known as fallouts of pixels in the video frame, where some elements of the bitmap file matrix [B] might have a significantly high readings. The following algorithm was applied in order to remove these pixel fallouts from the entire record.

\[
B_{i,j} = \begin{cases} 
\text{Il} & \text{if } B_{i,j} \geq \text{Ilcutoff} \\
\text{IlB} & \text{otherwise}
\end{cases}
\]

(2)

where: \( \text{Ilcutoff} \) is the specified lower cutoff parameter.

The next step was to compute the sub-matrix \( C_{ij} \) which included the nonzero components of \( A_{ij} \), and apply a bounded frame of 25 x 25 pixels on the \( C_{ij} \), zeroing the rest of the terms, and extracting the [C] matrix for further processing. This may be shown in matrix form as follows:

\[
[B] = \begin{bmatrix}
[0] & [0] & [0]
\end{bmatrix}
\begin{bmatrix}
[0] & [C] & [0]
\end{bmatrix}
\begin{bmatrix}
[0] & [0] & [0]
\end{bmatrix}
\]

(3)

The above mentioned process was performed for the entire record including the calibration frames where two LED lights were lit; this was used in order to correlate the pixel number with the known distance between the two centers of the LED’s and hence calibrating the movement of the target LED by developing a scaling factor to correlate the physical distance to pixel counts.

The next step was to perform a nonlinear Gaussian regression curve fit, in accordance with the following equation, which was subsequently utilized to determine the center of the high intensity red spot:

\[
f = a \times e^{\frac{-(x-x_0)^2}{b} + \frac{(y-y_0)^2}{c}}
\]

(4)

The Gaussian regression is to determine the values of \( a, b, \) and \( c \). Then the program calculates the peak value of the curve for each frame, and develops a frame of 25 x 25 pixels around the red target. Figure 4 shows the result outcome of the data processing for each frame.

The peak values resulting from the nonlinear Gaussian regression of each bitmap file were then extracted and stored in a file to be tracked as a function of time. The optical center area of interest was automatically updated for each frame utilizing Gaussian regression. This procedure was repeated for each frame, for the entire recorded data set. Upon completion, all the peaks of the Gaussian curve fits were stored in single file. The entire record was read and signals processing was performed in order to smooth the data.

The first signal processing step performed on the raw data mentioned above was to remove the mean. The next step was to digitally filter the de-meaned signal, using Fast Fourier Transform (FFT) techniques. A high-pass filter value of 0.01 Hz and a low-pass filter value of 5.0 Hz were used. Finally a cosine squared filter function was applied to the leading and trailing portions of the single in order to smooth the start and end of the record.

The program then stores the motion of each frame throughout the entire record. In order to calibrate the movement of the target, a known distance between two red lights was recorded at the beginning of each

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recording. The above-mentioned procedures were performed for both red lights in one frame and the number of pixels between those two lights were correlated to the known distance of these lights. The following figures show the results of the data processing. Figure 5 shows the displacement time history record corresponding to the entire record of the optical center data after the signal processing. Note the displacement of the bridge ranged from 1.5 to 2.2 inch. This motion range is consistent with what other investigators have estimated for the ambient motion of VTB.

It should be noted that the FFT of the entire record for the center measurement detected the first two dominant modes of the bridge. The first mode is at 0.23 Hz and the second at 0.36 Hz. These modes closely match those obtained by other studies using system identification techniques in conjunction with ambient vibration measurements from the sensor array discussed earlier.

DISCUSSION

This study has demonstrated the potential of vision-based approaches for the direct measurement of the time history of selected locations on a large civil infrastructure system. Some difficulties were encountered during the field experiment which will need to be addressed in the future. The mounting location of the video camera on the bridge was not ideal. The camera was affected by the high frequency generated from the on-going traffic. A better rigid attachment location on ground level would optimize the picture quality and field of view. In addition the angular orientation of the camera with respect to the bridge was not addressed. This could be easily resolved if the camera is placed on the ground and triangulation calculation is performed in obtaining the bridge movement. Finally the camera used was a standard household type of camera with high resolution. However, a professional video camera with a higher resolution could significantly improve the picture image. The targets were equipped with low-power LED’s, which were initially battery operated. It will be necessary to experiment with different types of LED color and intensities. As previously indicated, this study used a pattern of red LED's with a black background; however, the ambient conditions in the vicinity of the Vincent Thomas Bridge such as rain, dust or light noise from the surroundings may dictate a different setup.

SUMMARY AND CONCLUSIONS

An overview is presented of an analytical and experimental study into the feasibility of a novel vision-based approach for obtaining direct measurements of the absolute displacement time history at selectable locations of dispersed civil infrastructure systems such as long-span bridges. The measurements were obtained using a highly accurate camera in conjunction with a laser tracking reference. Calibration of the vision system was conducted in the lab to establish performance envelopes and data processing algorithms (particularly integration-related issues) to extract the needed information from the captured vision scene. Subsequently, the monitoring apparatus was installed in the vicinity of the Vincent Thomas Bridge in the metropolitan Los Angeles region. This allowed the deployment of the instrumentation system under realistic conditions so as to determine field implementation issues that need to be addressed. It is shown that the proposed approach has the potential of leading to an economical and robust system for obtaining direct, simultaneous, measurements at several locations of the displacement time histories of realistic infrastructure systems undergoing complex three-dimensional deformations.

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