Viability of optical tracking systems for monitoring deformations of a long span bridge

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ABSTRACT

Characterisation of both dynamic and quasi-static deformations of suspension bridges is essential to manage their serviceability and to appreciate the internal forces due to the various live loads effects of wind, temperature and traffic. GPS is commonly used for the largest, most flexible structures but the limitations are not well understood and accelerometers cannot capture the extreme low frequency movements. Optical displacement tracking has potential to avoid all these errors but has different types of limitation that need to be evaluated and mitigated. In attempt to cross-validate optical tracking technology against GPS data, a commercial optical system the Imetrum 'Video Gauge' was used at Humber Bridge, after first initial experiments on a short span bridge to identify the most effective way to deploy it in the field for measurements at very long range. Some results are presented illustrating the character of the observed deformations and the limitations of the various forms of deformation monitoring instrumentation. In particular limitations of GPS were highlighted through comparison with Video Gauge and accelerometer data.

Keywords: *bridge monitoring GPS acceleration optical*

1 INTRODUCTION

Bridge performance can be characterised via a number of metrics such as strains and accelerations, but perhaps the most useful metric of all is deformation, since practically all other metrics can be derived from it via differentiation in space (giving strain) or time (giving velocity and acceleration).

Serviceability is also reflected through deformation, since extreme values and ranges indicate problems that may limit operational use, such as at movement joints. Measurements of deformation also provide direct calibration of numerical simulations of load/response relationships via load tests and monitoring of performance e.g. in strong winds. Deformation measurements also provide a powerful diagnostic tool, for example for investigation of the truss-end link that closed the Forth Road Bridge in late 2015 [1].

Choice of technologies for bridge deformation measurements [2] depends on the factors that include the spatial range/resolution, sample rate/frequency response, number of axes and stability of fixed references. While uniaxial movement across bearings and expansion joints can be measured using LVDTs and short range lasers, tracking deformations in bridge spans is more challenging. For

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short span bridges over accessible land, LVDTs can also be used, leaving long spans over water and inaccessible open space. Options include total stations [3], GPS [4], hydraulic level sensing [5], integration of tilt or acceleration [6] and systems based on image recognition and tracking [7]. While GPS has become the standard technology, it has limitations, particularly for shorter spans where movement ranges are modest. Hence the non-standard techniques using image tracking, acceleration integration and total stations have potential to provide more reliable information.

Limitations of more traditional displacement tracking technologies have driven research into bridge deflection measurement using vision based systems, supported by advances in image processing algorithms in the past decade. Some of these systems require a specific target to be placed on the bridge (e.g. [8]), while others such as the commercially available Video Gauge used in this paper can also use structural features (with appropriate texture/contrast). Optical systems use the same fundamental approach: In the first frame of the video the user defines a zone or points in the image to track (e.g. the mid-span of a bridge), the algorithm then tracks the (pixel) coordinates of the pixel zone of interest between successive frames. Conversion from pixel size to full scale depends on either a known distance to and angle of the target, or known target dimensions.

One of the earliest applications of vision-based structural deformation monitoring was to the Humber Bridge in 1990 [7] which used the ancestor of the system described in this paper. Since then a number of systems have been developed and evaluated for structural monitoring. For example, Lee and Shinozuka [9] and Feng et al. [10] developed vision-based systems to monitor the two-dimensional displacement of bridge based on scaling factor transformation, working on the assumption that the optical line of sight is perpendicular to the bridge motion of interest. Chang and Xiao [11] proposed a single-camera system to extract the motion of a short-span pedestrian bridge; the three-dimensional motion could be obtained in theory but the displacement perpendicular to the target plane is not reliable. A telephoto lens was used in the long-span suspension bridge [12] where instead of fixing the camera to solid ground, four LED control points were arranged at the tower foundation and the camera was installed at the mid-span of the bridge.

Vision-based systems have sometimes been applied to in-plane motion monitoring of bridge stay cables without using an artificial target [13,14]. Stay cable vibration is the rare example where expensive LDVM –using line of sight measurement- is a viable technology for rapid assessment of cable tensions [15].

Despite the rapid advances in image processing technology and the successful applications of the technology to bridge displacement monitoring reported above, challenges remain. In particular issues around camera stabilisation and varying light levels need to be investigated and these are reported on in section 2.

2 DESCRIPTION OF SYSTEM AND EARLY RESULTS (SHORT SPAN BRIDGES)

The ultimate goal of this paper is to examine the ability of a commercial optical system, the Imetrum Video Gauge [16] to track accurately the displacement of a long span bridge. Similar to other optical displacement tracking systems very accurate results have been reported in the laboratory. However, environmental conditions in the field are different to those of the laboratory therefore before attempting to capture displacement of a long span bridge a series of preliminary field experiments were carried out in Exeter. In particular the ability of the system to capture displacements of a short span bridge were examined. This testing was extremely worthwhile as the results observed lead to some modifications in deployment strategy which proved successful when deployed on a long span bridge. A summary of the preliminary testing is provided in this section. In particular the test procedure used, the results observed and the modifications implemented are reported.

2.1 Initial testing and results

The testing set up used in the Exeter field trial is shown in Figure 1. Video Gauge has the capability to record data from two cameras simultaneously so cameras were positioned on the north and south sides of the bridge. The southern camera was using an 180 mm lens and the northern camera had an 85 mm lens fitted. As the bridge is a painted steel girder there is very little natural texture in the image so for the system to be effective artificial targets were stuck to the side of the bridge to the bridge. As seen in the figure the 'target' comprises a series of black and white concentric circles.

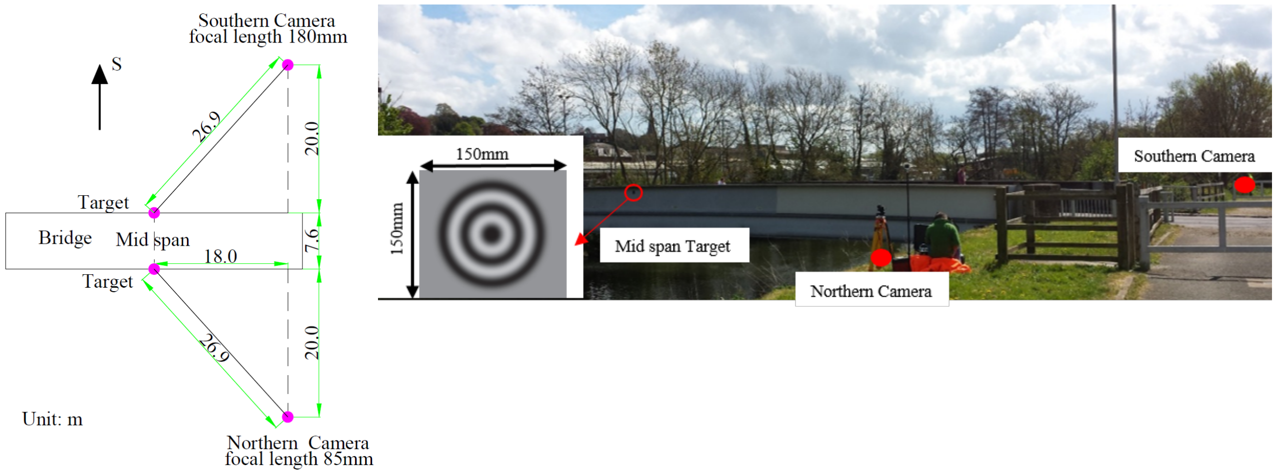


Figure 1. Field trial of Video Gauge. Arrangement of cameras (left) and bridge tested (right).

Dimension lines marked on the target were used as references to calibrate the coordinate frames in the image processing software. The horizontal displacement (at mid-span) returned by the system (over 400 seconds) for the north and south sides of the bridge is shown in Figure 2. Extraneous high frequency noise and a low frequency drift is evident in both plots. However there are no significant features in the time history and engineering judgment tells us the bridge should not be moving horizontally as much as ±1.5 mm horizontally.

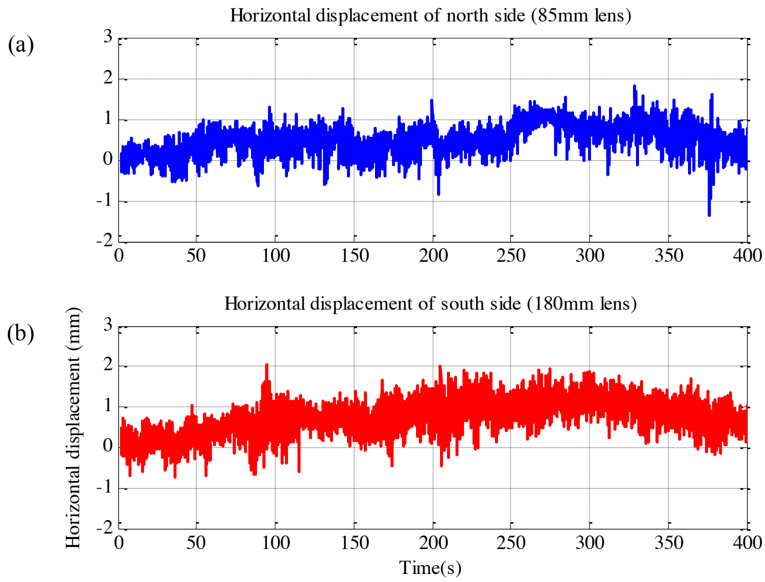


Figure 2. Horizontal displacement (mm) reported by system in first 400 seconds of the test, (a) north side of bridge, (b) south side of bridge.

The mid-span vertical displacement returned by the system for the north and south sides of the bridge are shown in Figure 3. The plots show the raw data and an overlaid 'average' plot, (using a moving average filter of an appropriate span). When the average plot in Figure 3(b) is examined it is evident that the displacement starts from zero, increases to approximately 1 mm after 250 seconds and then falls back toward zero. In this time there were a limited number of discreet vehicle crossing events, i.e. there was no credible loading pattern that could have caused such vertical deflection.

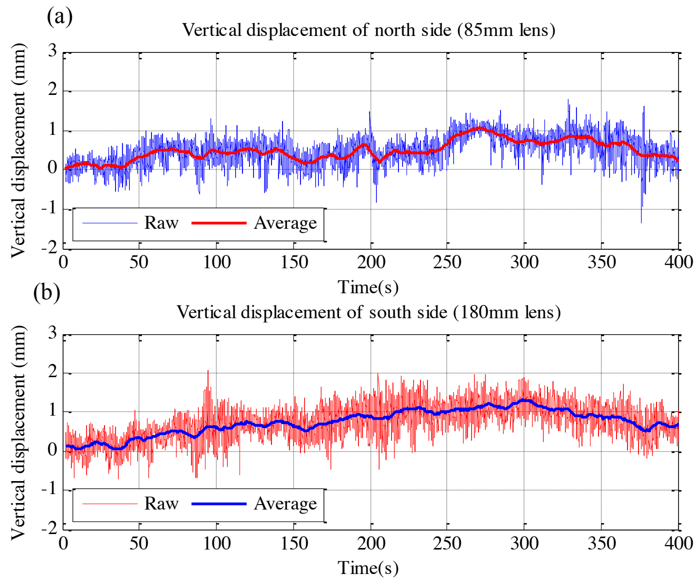


Figure 3. Vertical displacement (mm) reported by system in first 400 seconds of the test, (a) north side of bridge, (b) south side of bridge.

From a previous modal testing of the bridge it is known that the first bending and first torsion frequency of the bridge are at 3.1 Hz and 4.9 Hz respectively. The high frequency movement in Figure 3 does not look like conventional dynamic bridge movements and to confirm this, the frequency content is shown in Figure 4 but there are no peaks evident at 3.1 or 4.9 Hz. So, as with the horizontal displacement, the vertical data obtained in this video gauge deployment are not usable. Following discussion with the manufacturer it was brought to our attention that the noise/ drift experienced in the Video Gauge was likely due varying lighting conditions.

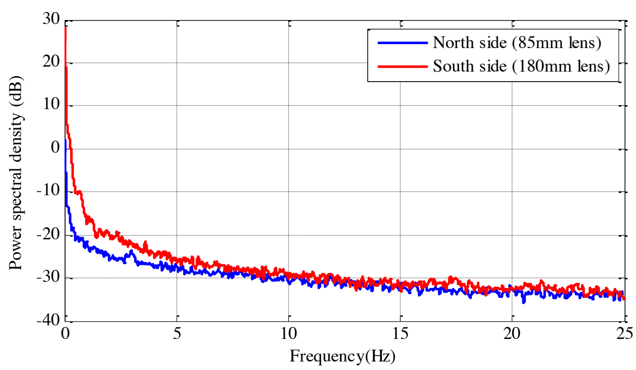


Figure 4. Frequency content of vertical displacement signals seen in Figure 3.

2.2 Modifications and improved results

From the preliminary study, the cause of the drift problem observed in Figure 2 and Figure 3 was believed to be due to changing lighting conditions, one of the significant issues with optical systems. Following the site work described in section 2.1 a software update with auto exposure feature was released. To examine if the auto exposure feature improved results the test described in section 2.1 was repeated and more stable/creditable results were achieved. Figure 5 (left) shows the revised test set up, this time with both cameras were pointing at the same target, Figure 5 (right). shows the mid-span vertical displacement measured during the test. Comparing Figure 5 to Figure 3 it is evident that using auto-exposure reduces the amount of noise and drift significantly. In this test the displacement stays around 0 mm, except at 50, 60, 100 and 110 seconds where single or multiple car/van events resulted in displacements in the region of 0.2 mm. Considering the structural properties of the bridge (material, section and span) and the approximate weight of a car/van, this magnitude of displacement makes sense.

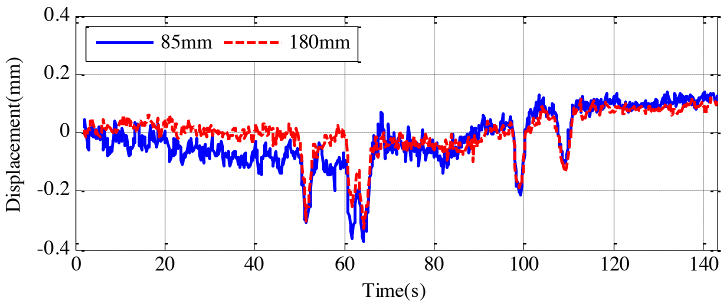



Figure 5. Repeat test configuration and results from test using auto exposure feature of the software.

From the testing described in section 2.1 we also formed the conclusion that the displacement results obtained in windy conditions were unsatisfactory so an improved, more rigid mounting was designed. Figure 6 (left) shows the original mounting of 300 mm lens, which is in effect a cantilever and Figure 6 (right) shows the newer more substantial mounting. Although wind is still an issue, more robust results have been obtained with the new mounting; the lens mounting is a critical feature of optics-based measurements. With these modifications to exposure and camera mounting the accuracy was satisfactory so we were confident to move on to measuring deflections on larger bridges, as described in the next section.

Figure 6. Lens mounting, (left) old approach, (right) new approach

3 APPLICATION ON A LONG SPAN BRIDGE: HUMBER

The Humber Bridge [2], opened in 1981, has a main span of 1410 m and side-spans of 280 m and 530 m. A single day of field testing using the vision-based monitoring system was used to measure the lateral and vertical displacement at mid-span of the bridge. The system performance is evaluated by comparing with a GPS 'reference sensor' in time domain.

In the field test, the camera and controller along with battery power supply, were located near the foundation of north (Hessle) tower shown in Figure 7(a). The lens used was the NIKKOR 300 mm f/2.8. A custom-made steel frame with the dimension of 1 m×1 m was mounted on the parapet at the mid-span shown in Figure 7(b). The pattern of the target is a set of concentric rings with a gradual blend from black to white at the edges. To ensure a reliable mounting condition, two C channels welded to the target frame were fixed to the top and the vertical railing of the parapet. Four ropes were tightened between the target and the railing to prevent out-of-plane rotation. The target was close to midspan, 710 m from the camera lens.

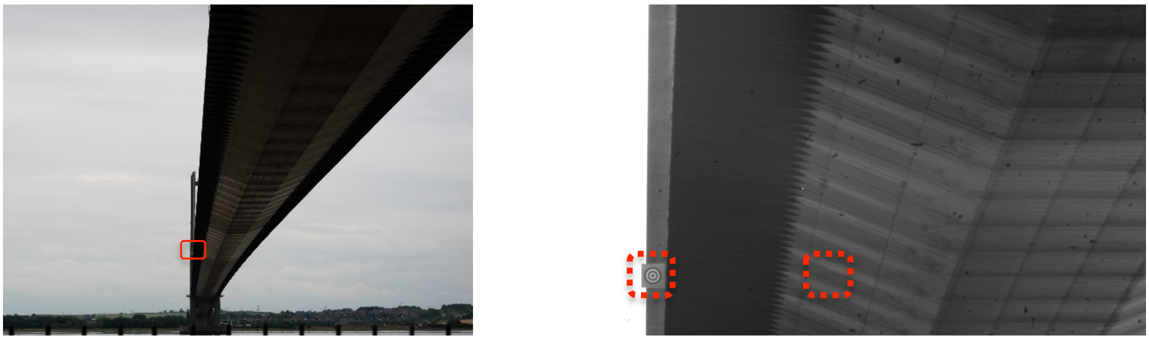
(a) Camera near tower foundation

(b) Custom-made target at mid-span

Figure 7. Video Gauge and target configuration in the test of Humber Bridge

The frequency range of interest was less than 1 Hz, thus the sampling rate was chosen as 10 Hz, fast enough to obtain the structural vibrations. In order to save storage space, the image was letterboxed with the size of each frame saved as 850×400 pixels, out of the default image size of 2048×1088 pixels.

Both the custom-made target and the feature target at mid-span were tracked by the image processing package. Figure 8(a) shows the view from the camera position, and (b) a single captured video frame. The red dashed boxes in the figure include the custom-made target and a natural target on the bridge soffit. The establishment of the transformation from physical coordinates to camera sensor coordinates is required. Assuming that the out-of-plane motion along the longitudinal direction of the bridge is negligible, projective reconstruction was conducted using three or more coplanar line correspondences. The lines with known dimensions came from the edge and diagonal of the installed artificial target frame.



(a) Targets viewed from the camera (b) Custom-made and feature targets

Figure 8. Custom-made target and feature target from the camera view

3.1 Measurement evaluation in time domain

During the test, a Nikon D800 D-SLR camera was used to video-record traffic on the bridge. Figure 9 (a) is one frame captured from the recorded video when two HGVs were approaching the mid-span from opposite directions. Figure 9 (b) shows the corresponding measurement by the 'Video Gauge' system in vertical direction, with vertical deflection at mid-span caused by the two vehicles reaching 221 mm. In general, the measurements by tracking two targets agree well; the vision sensor demonstrate similar performance for tracking either target.

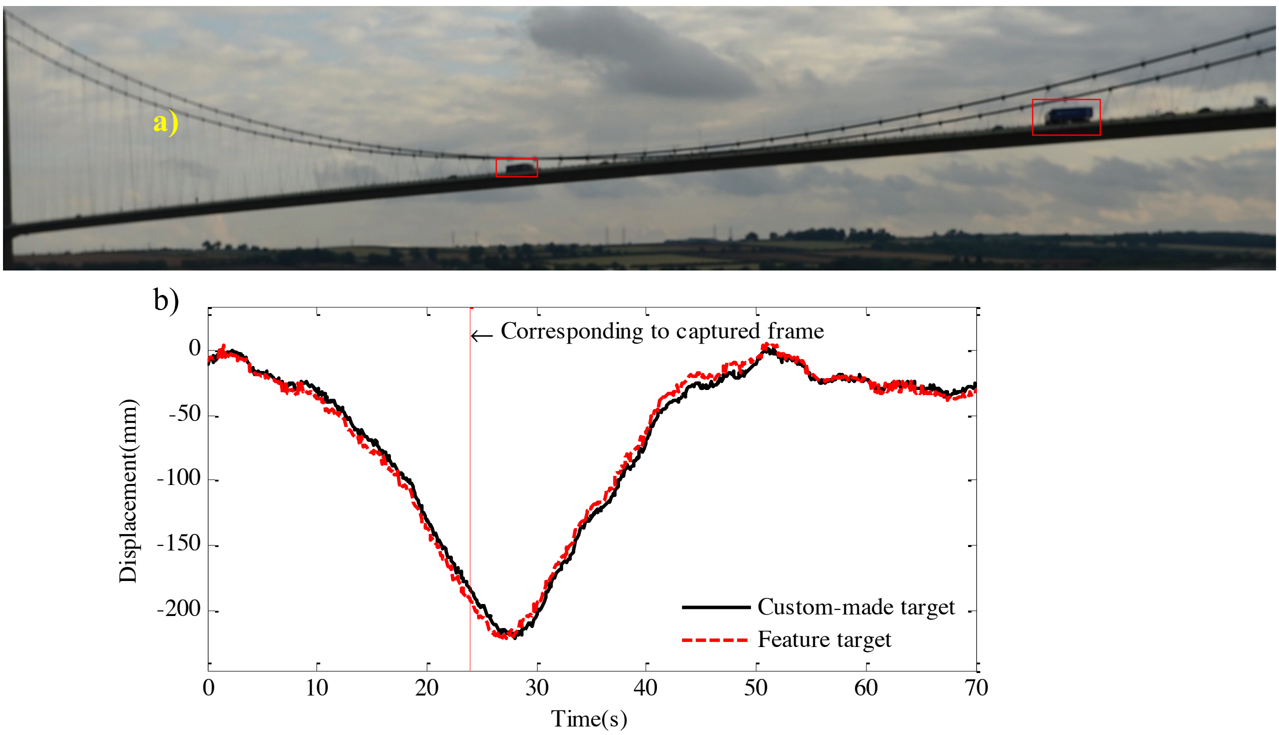
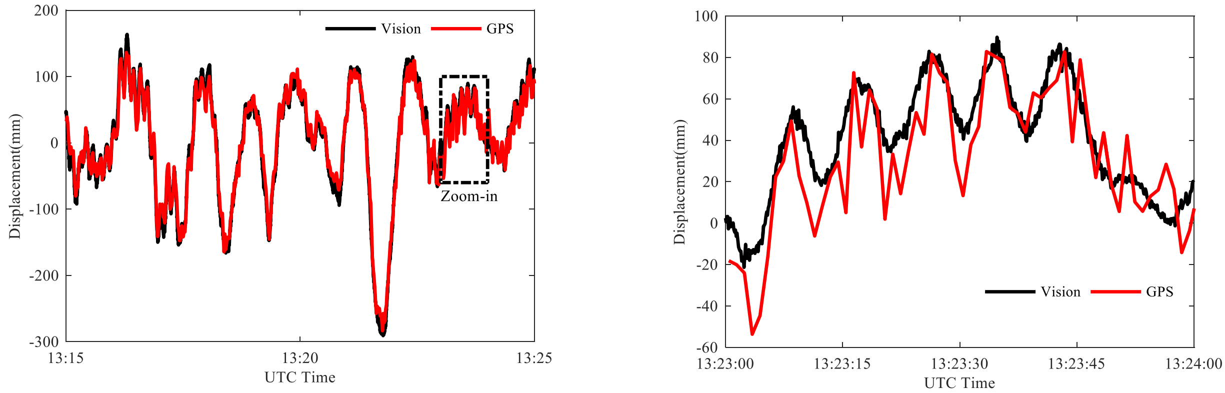


Figure 9. Measurement by Video Gauge when two vans approaching the mid-span. (a) Captured frame from a video with two vans approaching the mid-span, (b) Vertical displacement recorded by Video Gauge.

The long-term monitoring system of Humber Bridge, operational since 2010, includes GPS rover receivers at each side of mid-span [2], sampled at 1Hz. Figure 10 (a) shows the vertical displacement measurement by Video Gauge and the GPS receiver at mid-span.

Figure 10 (b) shows one-minute signals. The vision system had better performance in recording the low-frequency components, and the accuracy of GPS observation was in the centimetre-level.



(a) Ten-minutes of vertical displacement (b) Zoom of one minute of data in (a)

Figure 10: Comparison of vertical displacement by vision-based system and GPS

3.2 Measurement evaluation in frequency domain

Performance of the Video Gauge is also revealed in the frequency domain in Figure 11 which shows accelerometer data as acceleration vs. displacement signals.

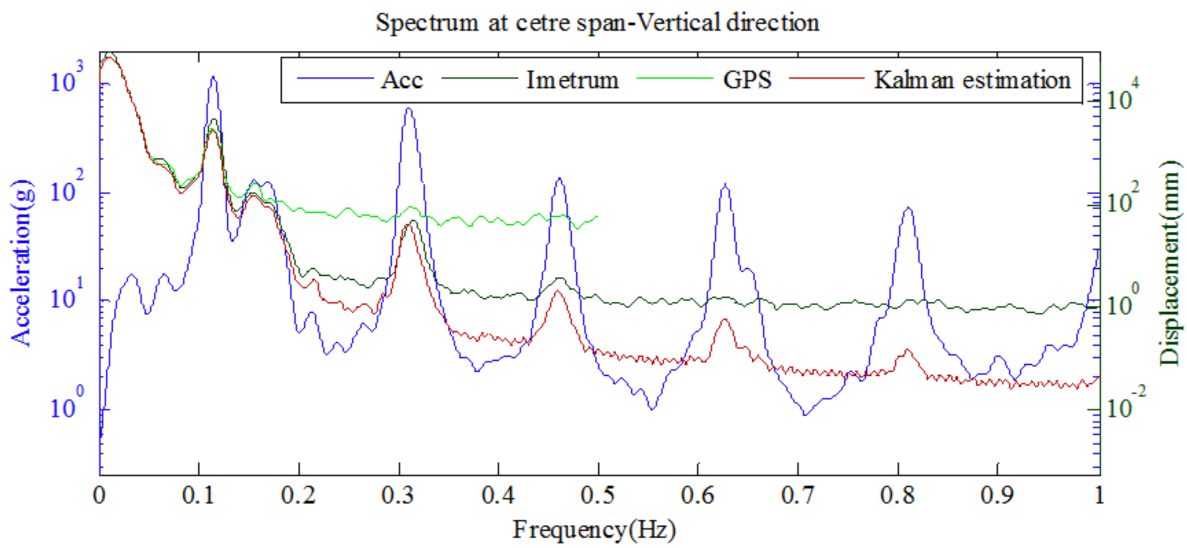


Figure 11. Comparison of frequency content of Video Gauge and other instrumentation.

The accelerometer signal is the most accurate representation of motion for frequencies above 0.1 Hz, but is not to be relied on for frequencies below 0.05 Hz. Also it is clear that the Video Gauge is less noisy above 0.05 Hz and can capture vertical modes that GPS cannot. The Video Gauge is also used to evaluate the reliability of combining GPS and accelerometer data using Kalman filter.

4 CONCLUSIONS

Accurate and reliable deformation measurement is an increasingly important capability for condition assessment of civil structures and new technologies require carful evaluation in real world conditions to iron out the bugs, identify limitations and factors on performance and build confidence in their use. So far optics-based monitoring has not been widely adopted but we see it as a major capability for the future of asset management through performance observation. Because the Video Gauge has a long pedigree (since 1990) and appears to be highly capable we have gone to considerable lengths to evaluate it through a series of experiments. We have confirmed the capability but have found this to be strongly affected by the way it is deployed.

Issues with lighting conditions have been mitigated with software upgrades but it remains necessary to take extreme care in providing a stable mounting for the lens and camera. Future evaluations will focus on extreme range and resolution, capability for who structure tracking, data fusion and more extensive comparison with standard technologies of GPS, robotic total station and accelerometers.

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