Case Study: Calculating Bridge Displacement from Accelerations for Load Assessment Calculations

Andrew Bunce[1], David Hester[1], Su Taylor[1], James Brownjohn[2], Yan Xu[2]
[1]Civil Engineering, School of Natural and Built Environment, Queens University Belfast,
Stranmillis Road, Belfast, BT9 5AG, Northern Ireland
[2]Vibration Engineering Section, University of Exeter, UK
email: abunce01@qub.ac.uk, d.hester@qub.ac.uk, s.e.taylor@qub.ac.uk,
j.brownjohn@exeter.ac.uk, yx298@exeter.ac.uk

ABSTRACT: Recovering displacement from accelerations has been demonstrated on bridges previously, with the main challenges being the presence of low frequency noise and the need for user-calibrated filters to overcome this. Therefor this paper presents a case study of a low-cost load test procedure, using bridge acceleration to calculate displacement. Typical approaches look use filtering or signal correcting methods to mitigate noise, however this study uses an aviation grade accelerometer to minimise noise in the acceleration signals and employs a quality control procedure to alert the user to the quality/reliability of the results. A live/open bridge is tested using a loaded and unloaded truck, and direct displacements are also recorded by linear variable displacement transducer (LDVT) and Imetrum camera displacement system to verify results. The calculated displacements from the integration procedure with varied loads are presented, with the quality indicators first being assessed before comparing to the directly measured displacements. This procedure may not be applicable to longer span bridges, or bridges where it is difficult to isolate quiet periods of traffic, however for this study the procedure worked well. Overall, the quality indicators provided good insight into the accuracy of the calculated displacements and there was good agreement between the 3 measurement methods, with the magnitudes of errors experienced being around ±0.3mm

KEY WORDS: Bridge SHM, Displacement, Acceleration, Integration, Load Testing

1 INTRODUCTION

Choices in displacement tracking methods for bridges are often made depending on the site/bridge to be monitored. In a small number of instances, it is practicable to use traditional approaches such as linear variable displacement transducers (LVDTs), provided a fixed reference is accessible enough to measure from For scenarios where this is not the case, image-based approaches have become increasingly popular [1, 2], though these methods can be expensive, are sensitive to weather and often require high levels of user expertise to successfully implement.

Other novel approaches have been developed that look to capture displacements by twice integrating acceleration signals. The main difficulty with recovering displacements from acceleration signals is due to the presence of low frequency noise in the acceleration signal [3, 4], which are amplified during the integration process.

There has been extensive research looking to remove the effects of noise in the acceleration signal, such as Faulkner et al. [5], who used a baseline correction method (BCM) and high pass filter to estimate noise in the displacements of a bridge subject to a moving load. With the appropriate filter, the method proved successful, however the repeatability of the method was limited owing to a lack of guidance on selecting the appropriate passband frequencies for different bridges.

Similarly, Park et al. [6] displayed a velocity estimation method that required acceleration signals to be cut into short segments and have a high pass filter applied for accurate estimates of displacement to be achieved. Gindy et al. [7] used a state space correction method for correcting the noise effects in acceleration signals. Although both procedures showed promising results, those results were dependent on user selected input parameters and relied on expertise/experience of the user for successful application to further bridges without guidance.

Sekiya et al. [8] proposed cutting acceleration signals to short windows before using high and low pass filters to reduce the presence of noise. Filter inputs were estimated based on factors such as vehicle speed limits and bridge spans (and hence loading durations). Multiple MEMS accelerometers were tested, and varying quality of results were obtained which showed to be dependent on the quality of sensors used. The filtering technique’s success was reliant on the quality of sensor as well as the filter inputs and signal truncating.

The quality of chosen hardware and duration of loading are key influences on the accuracy of displacement estimates from acceleration signals. Therefore, here we display a procedure proposed in [9] that does not rely on filtering methods and instead uses high quality accelerometers (to minimise noise) and also implements a quality control check to assess the quality and hence reliability of the calculated displacements. This paper presents a case study of the procedure being applied to a live bridge, comparing results obtained from a load test using a (i) loaded and (ii) unloaded truck.

2 BACKGROUND THEORY

Figure 1(a) shows midspan displacement results from a Matlab model of a beam and moving point load, intended to represent a bridge and moving truck for demonstration purposes. The load enters the beam at 2.5 seconds and leaves at 7.5 seconds, moving at a constant rate. The displacement in (a) is annotated with the preload and post load portions of the displacement (blue), where the signal remains close to 0 for the unloaded portions, and with the forced displacement (red) where the displacement peaks at 2.8mm at 5 seconds. When differentiated, the effect of the forced displacements can be seen on (b) velocity and (c) acceleration, where at each stage the static effects of the moving load are less apparent.

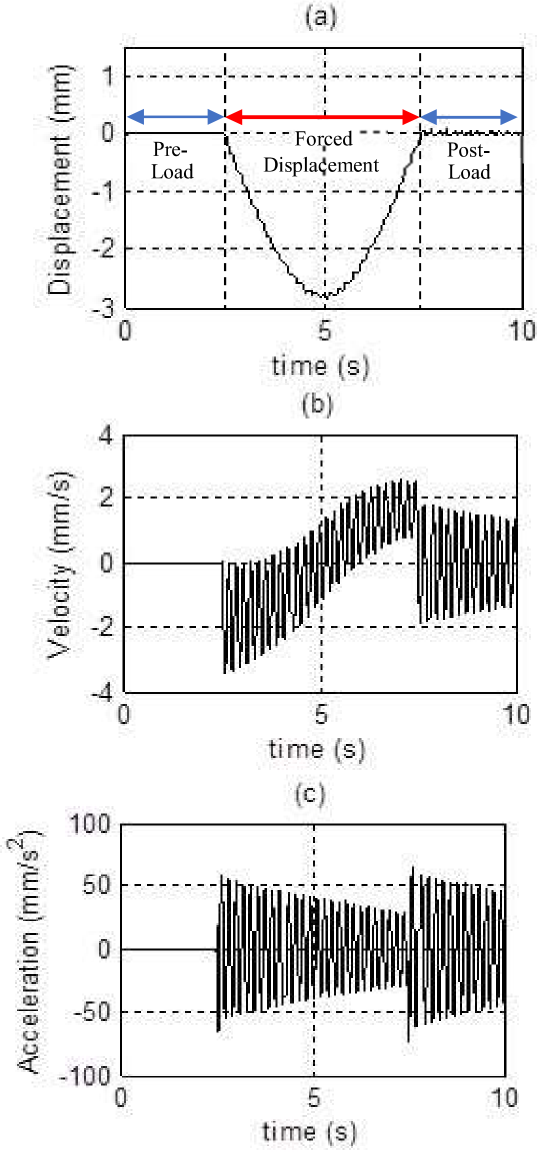


Figure 1. Results from a model of a beam subject to a moving load, (a) displacement (with pre-load and post load annotated in blue, and forced displacement annotated in red), (b) velocity, and (c) acceleration.

Whilst the acceleration is typically easier to measure than displacement, the fundamental issue when looking to integrate acceleration to recover displacements is the low frequency noise that will exist in the acceleration signal. The low frequency noise in the acceleration signal causes amplified errors in the displacement results when integrated, and this can cause exponential drifts in the results, masking any true displacements. Overcoming the effects of the accelerometer noise can lead to accurate recording of displacements without the logistical challenges present with more traditional methods.

3 TEST BRIDGE AND TRUCK

The truck used in the test was a 4-axle Scania P410. Figure 2(a) shows a photo of the truck, Figure 2(b) shows the layout and axle weights for the loaded truck, and Figure 2(c) shows the axle weights for the unloaded truck. The bridge used in this study is a 3-span beam/slab bridge with each span simply supported. Figure 3(a) is an elevation showing the 3-span bridge. The span to the right was used in this study, as the exposed sand bank allowed for an LVDT system to be installed to verify the calculated displacements. Figure 3(b) is a cross section of the bridge deck with encased steel I beams at 1.54m centres and showing corresponding lane layout. Figure 3(c) is a plan view of the bridge deck showing lane layout and highlighting the monitoring location. Owing to the road layout, the truck used lane 4 on the bridge which allowed for the most passes in the shortest time period.

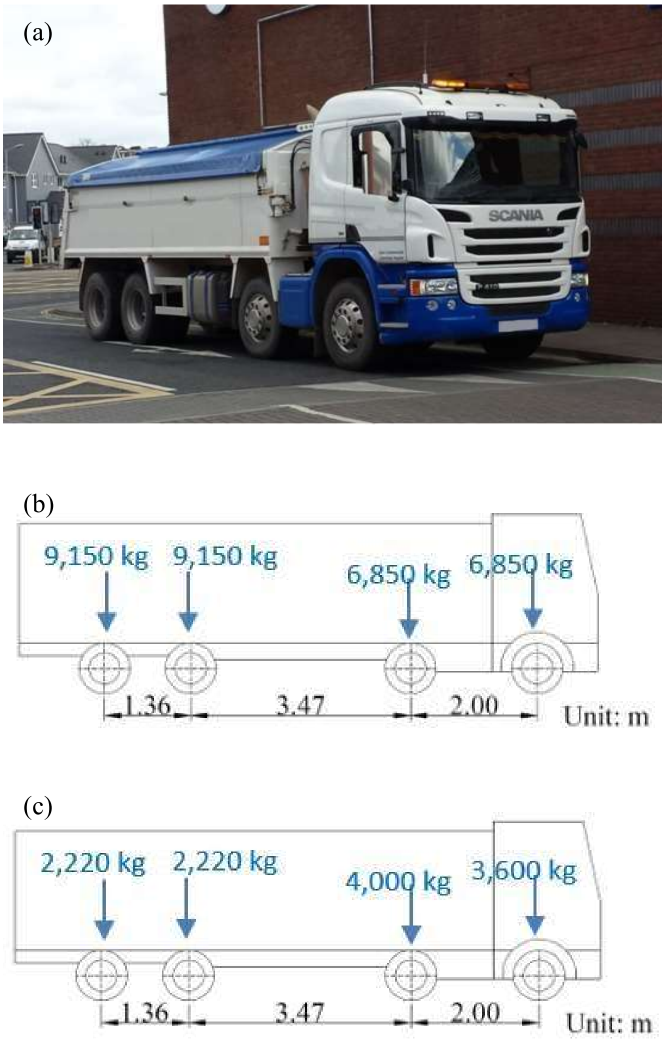


Figure 2. Truck used in test (a) photo of the Scania P410 used and (b) axle loads of loaded truck, (c) axle loads of unloaded truck.

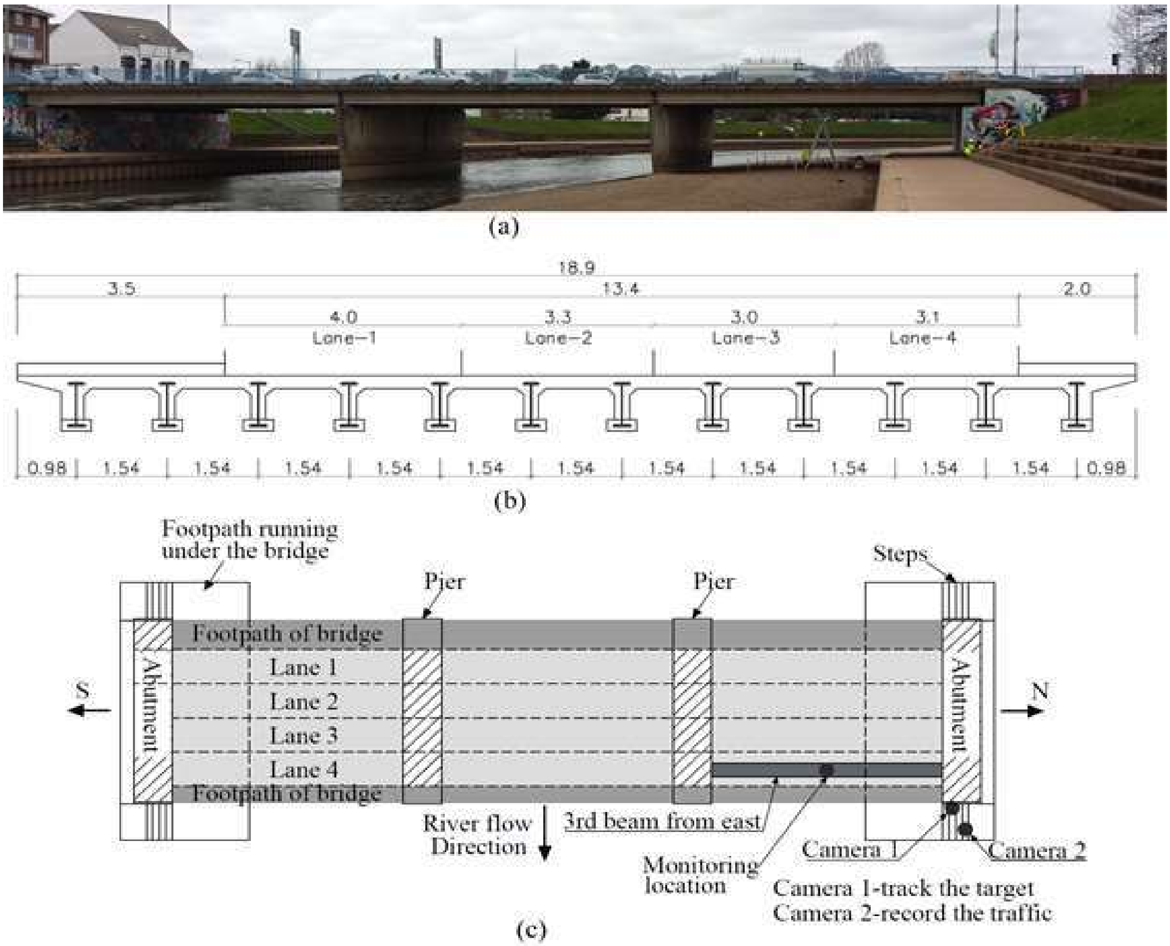


Figure 3. Bridge used in load test (a) East elevation showing 3-spans of the bridge, (b) typical section of the bridge deck, (c) Annotated plan view of bridge deck highlighting monitoring location.

4 SENSORS INSTALLED

The accelerometer used in this test was a Honeywell QA 750 accelerometer, an aviation grade force balance accelerometer. The reason for using this sensor is that it has low noise levels (<0.000069 m/s²/√Hz (0-10 Hz) and <0.00069 m/s²/√Hz (10 - 500 Hz)) which should help minimise errors in the calculated displacement due to noise. The sensor was mounted in Perspex housing and fixed via a steel angle to the soffit of the third beam from the east side of the bridge (Figure 5).

To provide check measurements for the displacement calculated from the acceleration signal, two independent measurement systems were co located with the accelerometer, namely an LVDT and an Imetrum camera system. Figure 4 shows an overview of the bridge site as the test truck passes over the bridge and Figure 5 shows a close up of the instrumentation attached to the underside of the bridge beam. The circular ‘targets’ on the side of the accelerometer in Figure 5 are to provide enough texture/contrast in the image to allow the Imetrum camera system to track the displacement. The LVDT was fixed to a telescopic aluminium pole, with a small dimple in the steel angle housing the LVDT tip.

In Figure 4 the Imetrum camera tracking displacement is in the bottom right of the frame and the telescopic pole supporting the LVDT just visible to the left of the ladder under the midspan of the bridge.

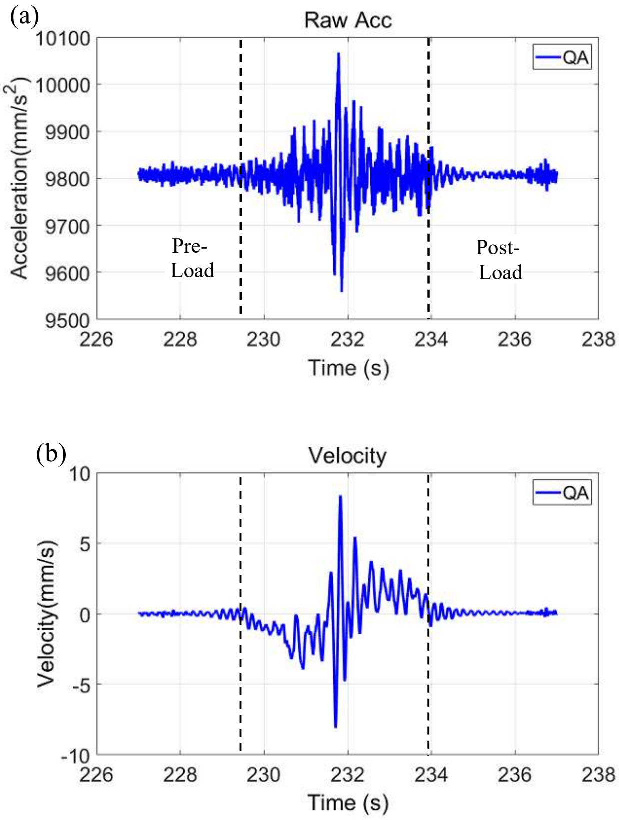
Figure 4. Monitoring installation on bridge as truck passes over midspan during Loaded Swipe 1

Figure 5. Instrumentation on the underside of the bridge beam.

5 RESULTS

The test for this study comprised of a number of passes of the loaded and unloaded truck. Figure 6 shows a sample of the integration procedure applied to the first pass of the loaded truck. Figure 6(a) shows the detrended acceleration signal cut to a short window duration, including preload and post load accelerations in the signal marked 229.3 seconds for the truck entering and 234 seconds for the truck leaving. Figure 6(b) shows the velocity calculated by integrating the acceleration from (a), and (c) shows the displacement calculated by integrating the velocity from (b). Figure 6(d) shows the same calculated displacement from Figure 6(c), plotted with the displacements measured with the Imetrum (magenta) and LVDT (cyan) systems.

The preload portion of the calculated displacement (Figure 6(c)) remains close to 0mm as the truck approaches the bridge and returns to close to 0mm after the truck has left the bridge. Using this as a quality check on the results would indicate a reasonably accurate displacement estimate for the trucks passage. Figure 6(d) reproduces the calculated displacement from Figure 6(c) (blue) and also plots the measured displacements from the LVDT (cyan) and Imetrum system (magenta), where the quality check is then verified by the good agreement between the 3 displacements for the duration of the window, with only small differences in the return shoulder.



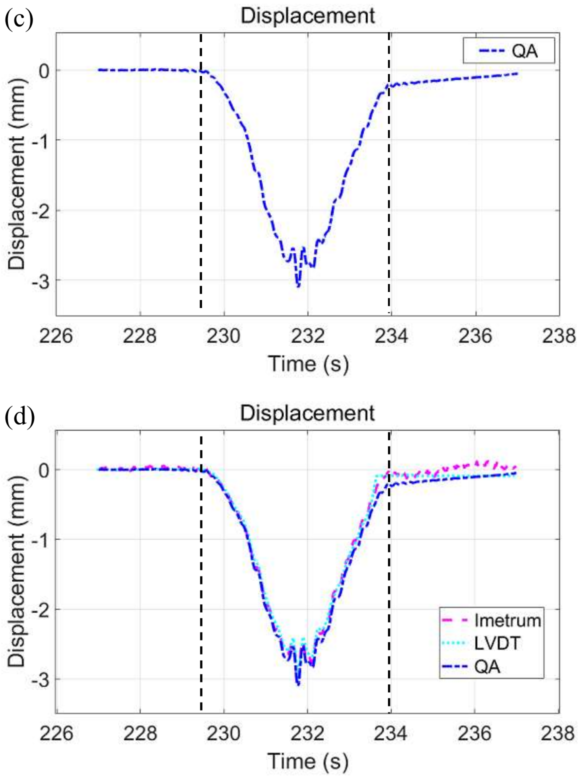


Figure 6. Displacement from first pass of loaded truck (a) detrended acceleration, (b) velocity from acceleration, (c) displacement from velocity and (d) QA displacement (blue) plotted against LVDT (cyan) and Imetrum (magenta) displacements.

Figure 7 shows the displacements from the second pass of the loaded truck test. Broadly speaking, there was good agreement with all 3 measurement methods again. The errors from the loaded truck passes were small, in the order of 0.2mm for pass 1 and 0.25mm for pass 2. The shoulders of the displacement were relatively close to 0mm, suggesting good accuracy in the results, which was verified by the Imetrum system in both cases and the LVDT in the first. There was a slip of the LVDT (the tip jumped out of the recess) during the second pass of the truck at around 338s, but the QA showed good agreement with the LVDT to this point and with the Imetrum beyond here.

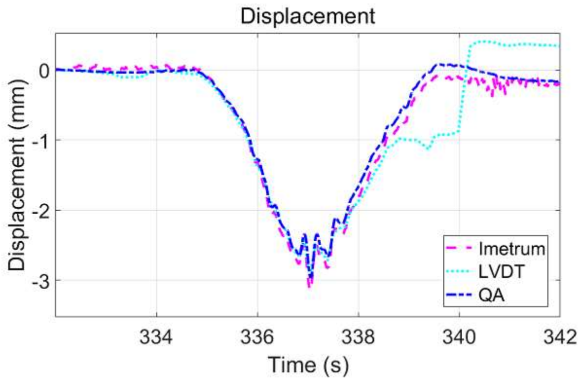


Figure 7. Displacements from second Loaded Truck pass with QA (calculated) displacement (blue), LVDT displacement (cyan) and Imetrum displacement (magenta).

The results of the two unloaded truck passes are shown in Figure 8. For the unloaded truck passes, the results also provided reasonably good estimates for displacement from the truck passing. There was a slip of the LVDT in the first unloaded pass, but the Imetrum measurement prevented this being of consequence. For the first pass, the first "shoulder" of the data started close to 0mm but did drift up slightly, which would alert to small inaccuracy in the loaded portion of the results, as verified with the Imetrum measurement however, the error was small, in the order of 0.2mm.

The calculated displacement from the second pass also showed a small drift upward in the first "shoulder", and the return shoulder did not return to 0mm, but this is believed to be because there was other traffic on the bridge which forced displacements. This was verified by the fact that the Imetrum and LVDT results also did not return to 0mm. The results from all 3 measurement methods again showed good agreement for the most part, with small amounts of drift present in the calculated displacement.

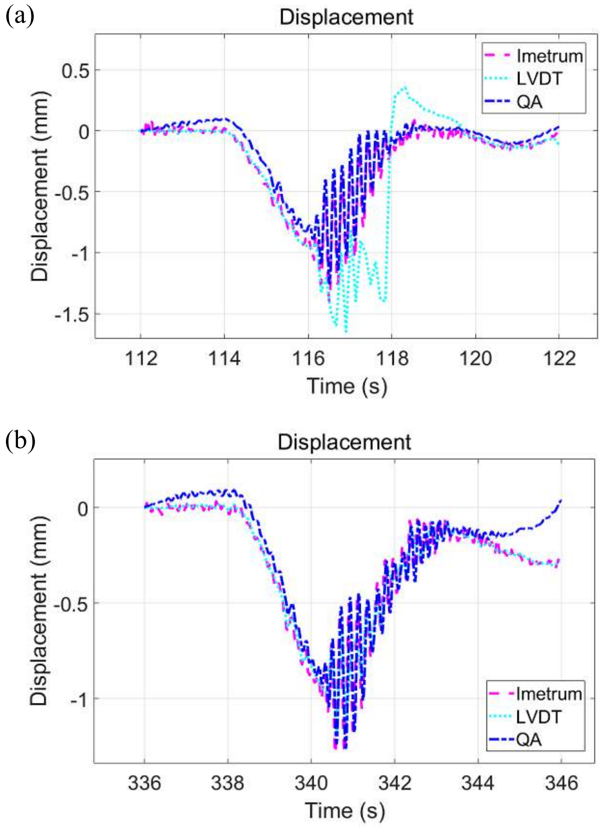


Figure 8. Displacements from Unloaded Truck from (a) pass 1 and (b) pass 2 with QA (calculated) displacement (blue), LVDT measured displacement in cyan and Imetrum measured displacement in magenta.

The pre-load and post-load portions of the calculated displacements provided a good indication of the reliability of the loaded portion of the calculated displacements for all the tests. For the quality control check to be successful, however, traffic conditions needed to be known for the time of testing as was experienced with the second unloaded pass. Since the quality indication requires no heavy traffic immediately before or after the load passes, there are logistical challenges with implementing this test on a live bridge.

6 CONCLUSIONS

This paper provides a case study of a procedure that uses raw acceleration data, and twice integrates to calculate displacement induced from a moving load. The method cuts the acceleration signal to include a short portion before and after the load passes and uses the pre-load and post-load portions of the displacement results to assess the likely reliability of the displacements.

The integrations procedure worked well using both a loaded and unloaded truck for the test, and there was little variation in the accuracy of the displacements estimated. The use of high-quality accelerometers and short duration loading helped to minimise the effects of noise in the acceleration signals, with the largest errors being around 0.3mm. The quality control check for the pre-load and post-load portions of the calculated displacements indicated relatively accurate results for each test with small signs of drift in the shoulders of the displacements. This was verified against displacements measured using an LVDT and Imetrum camera system, showing good potential for using the preload and post load displacements to assess the likely accuracy of the loaded displacement.

The procedure worked well in these circumstances, where for the most part (i) the signals being analysed were relatively short duration and (ii) the traffic flow was such that typically there were periods of known zero displacement either side of the loading/truck passing which could be used for quality control checks of the signal.

This may not be the case for other bridges of longer spans where longer durations of loading and hence acceleration signals will see larger effects of noise when integrated. For shorter span bridges, however, where periods of low traffic levels can be isolated and utilised, this procedure provides a viable solution to low cost displacement measurements for bridges where more traditional approaches are less practicable.

ACKNOWLEDGEMENTS

The research and work leading to these results was supported by EPSRC DTP grant EP/R513118/1 and also received support from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement no 330195.

REFERENCES

[1] "Imetrum - Road Bridges." https://www.imetrum.com/support/case-studies/structural/road-bridges/ (accessed Jun. 03, 2020).

[2] D. Lydon, M. Lydon, S. Taylor, J. M. Del Rincon, D. Hester, and J. Brownjohn, "Development and field testing of a vision-based displacement system using a low cost wireless action camera," Mech. Syst. Signal Process., vol. 121, pp. 343–358, 2019, doi: 10.1016/j.ymssp.2018.11.015.

[3] S. C. Stiros, "Errors in velocities and displacements deduced from accelerographs: An approach based on the theory of error propagation," Soil Dyn. Earthq. Eng., vol. 28, no. 5, pp. 415–420, 2008, doi: 10.1016/j.soildyn.2007.07.004.

[4] F. Moschas, D. Mouzoulas, and S. Stiros, "Phase errors in accelerometer arrays: An analysis based on collocated sensors and FEM," Soil Dyn. Earthq. Eng., vol. 78, pp. 32–45, 2015, doi: 10.1016/j.soildyn.2015.07.001.

[5] B. Faulkner, F. Barton, T. Baber, and W. McKeel, “Determination of Bridge Response Using Acceleration Data,” 1996.

[6] [6] K. T. Park, S. H. Kim, H. S. Park, and K. W. Lee, “The determination of bridge displacement using measured acceleration,” Eng. Struct., vol. 27, no. 3, pp. 371–378, 2005, doi: 10.1016/j.engstruct.2004.10.013.

[7] M. Gindy, R. Vaccaro, H. Nassif, and J. Velde, “A state-space approach for deriving bridge displacement from acceleration,” Comput. Civ. Infrastruct. Eng., vol. 23, no. 4, pp. 281–290, 2008, doi: 10.1111/j.1467-8667.2007.00536.x.

[8] H. Sekiya, T. Kinomoto, and C. Miki, “Determination method of bridge rotation angle response using MEMS IMU,” Sensors (Switzerland), vol. 16, no. 11, pp. 1–13, 2016, doi: 10.3390/s16111882.

[9] D. Hester, J. Brownjohn, M. Bocian, and Y. Xu, “Low cost bridge load test: Calculating bridge displacement from acceleration for load assessment calculations,” Eng. Struct., vol. 143, pp. 358–374, 2017, doi: 10.1016/j.engstruct.2017.04.021.