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Forced vibration testing of footbridges using calibrated human shaker and wireless sensors

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Abstract

Wireless inertial measurement units (IMUs) designed for biomechanical applications have been evaluated for modal testing of civil structures, in particular footbridges, where the small size and high response levels match the sensor capabilities. Building on research into recovery of ground reaction forces (GRFs) in walking and jumping directly using a treadmill or force plate, it has been found that a single carefully located IMU can successfully recover GRFs in open space conditions on full-scale structures. Amplitudes of first and second harmonics of the GRFs can be recovered with consistent and small bias errors by multiplying resolved vertical component acceleration by body mass.

Of the many potential applications, one with immediate use is the ability to carry out forced vibration tests without mechanical excitation. All that is needed is to record the acceleration of a structure along with that of a human jumping so as to generate a strong harmonic component at the structure's natural frequency. There are caveats involving identification of mode shape and satisfying requirements of the relevant system identification procedure, but the procedure has been applied successfully to two very different footbridges. The procedure and the results for these two bridges are described in the paper.

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1. Introduction

Numerical modelling is the only way to generate modal parameters for simulating linear dynamic performance of a footbridge at the design stage, but for a structure being retrofitted such as with a tuned mass damper, or that has ready for opening to the public, the most reliable values of modal parameters are recovered by in-situ testing. Such testing is usually logistical challenging due to the need to run signal cables and deploy heavy shakers that also need mains power or heavy battery capacity. Aiming to reduce the logistical complexity of such modal tests, the study described aimed to evaluate the capability of lightweight portable wireless MEMS accelerometers for synchronous acceleration measurements at multiple locations on a footbridge and of force generated by a human jumping (or walking) to generate dynamic response. It has been found that appropriate measurement of human body acceleration is enough to enable classical methods of experimental modal analysis with input/output signals.

2. Deployment of wireless inertial measurement units (IMUs)

A set of six Opal^{TM} IMUs is used with a wireless access point (WAP) to connect to a host computer (PC). Each MEMS IMU incorporates a magnetometer to sense orientation with respect to Earth's magnetic field, a triaxial accelerometer and a triaxial gyroscope. An IMU include wireless communication and on-board flash memory managed by a micro-controller. Information from the magnetometer and gyroscopes allow the accelerations to be resolved from IMU local coordinate system (LCS) to world coordinate system (WCS) including a purely vertical component, uncontaminated by cross-coupling from lateral acceleration.

In measurements described here the IMUs were used in *synchronised logging mode*, where acquired data are stored locally on the IMU timed by a local clock that is synchronized collaboratively by connecting to clocks of other IMUs. In this way IMUs can operate tens of metres apart like this. Data stored locally are downloaded using the docking station when the measurements are completed.

3. Baker Bridge

This first application of IMUs to capture both loading and response was at Baker Bridge (Figure 1), a 109 m cable-stayed bridge crossing the busy A379 dual-carriageway in Exeter. The bridge provides cycle and pedestrian access to Sandy Park Stadium, the home ground of Exeter Chiefs, a top-division rugby club. Because it is the sole pedestrian access from public transport the bridge experiences heavy pedestrian traffic on match days.

Figure 1: Baker Bridge.

The bridge comprises a single A-shaped 42 m tower supporting the deck via seven pairs of cables secured to the top of the tower; four cable pairs to a long front span on the (South) stadium side, two cable pairs to a short back span on the North side and one pair to a counterbalancing concrete mass at the North abutment. The deck comprises two 109 m Grade 50 steel 500x300x16 mm RHS longitudinal beams with transverse 150x150x5 mm SHS beams at 3.1 m centres all supporting the 120 mm in-situ reinforced concrete walkway. The six cables are secured to circular hollow section (CHS) that in turn support the longitudinal beams. The estimated total bridge mass is 150 tonnes.

4. Vibration measurements for modal parameter estimation

Baker Bridge was first evaluated by ambient vibration testing to estimate mode shapes, then by a mix of free decay and forced vibration testing to estimate modal frequency, damping and mass parameters, all using only the IMUs. Being the first application, standard sensing technology was used for cross-checking.

1.1 Ambient vibration testing (AVT) with IMUs for mode shape and frequency estimates

Ambient vibration measurements were made at a time of little pedestrian traffic. Before travelling to the bridge the set of six IMUs were set to acquire signals in the 2 g range, undocked from the base station and put in a jacket pocket for the short drive to the bridge. At the bridge a grid of 34 test points (TPs) indicated in Figure 2 was marked out by tape measure and chalk. Four TPs were at abutments or the tower where vertical motion was assumed to be zero. The IMUs were then ‘roved’ over 30 TPs in seven recordings as follows.

Two IMUs were kept at the same two references, TP13 and TP14. The remaining four IMUs were roved to cover the remaining TPs in seven recording sequences, with one example indicated in Figure 2. The whole exercise including gaps in the measurement sequence while moving IMUs took 67 minutes.

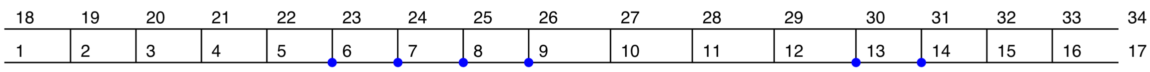

Figure 2: Locations of meaurement/test points (TPs), and TPs used for two of the seven five-minute recordings. QA force balance servo accelerometers were used in a parallel experiment.

Data were downloaded, split into a sequence of seven five-minute recordings and analysed using the NExT/ERA operational modal analysis procedure [2], producing set of modes presented in Figure 3. Mode 5 is almost pure torsion, with very little lateral movement.

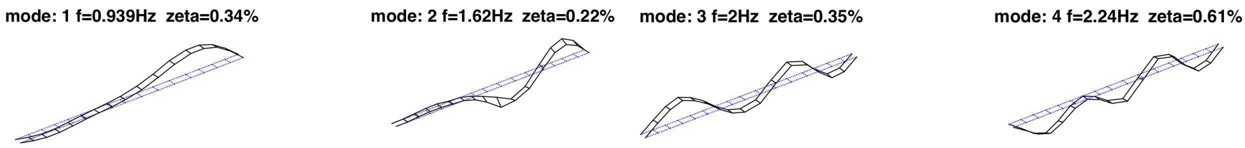

Figure 3: Mode shapes and frequency estimates from preliminary test. Longer front span is to the right in each mode.

5. Jumping tests for modal mass estimation

The signals in Figure 4 are an example of jumping on the bridge at TP13 to excite the first mode. The force data in Figure 5(a) are simply the vertical acceleration of an IMU attached at the sternum (breastbone) by the jumper mass (in this case 74 kg). This simple approach was expected to provide a rather crude representation – using a single strategically placed IMU, but it turned out to be surprisingly reliable for the purpose.

The best approach to generate large amplitude response is to jump between four and eight times at a rate corresponding to a reasonable estimate of the natural frequency, and then stop dead [1]. In Figure 4 a metronome was set to 54 beats per minute (bpm) corresponding to a frequency of 0.9 Hz. Figure 5(b) shows the corresponding acceleration response at TP13 where modal amplitude is largest.

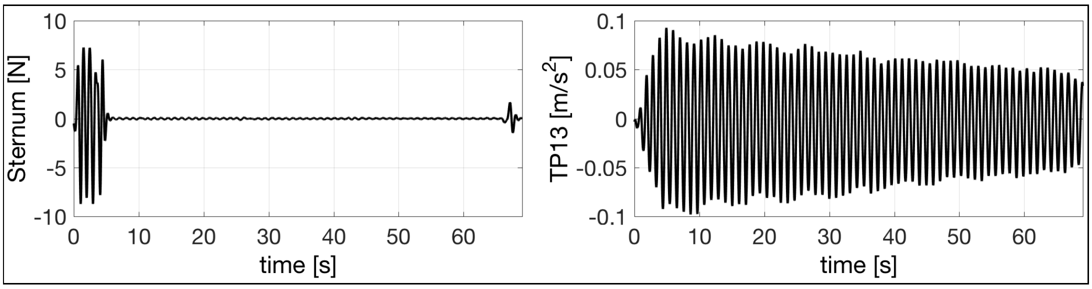

Figure 4: Estimated jumping force at TP13, via IMU attached to sternum of 74 kg jumper left), acceleration response at TP13 (right).

Force/response data can be analysed applying traditional frequency domain identification techniques, e.g. circle fit or global rational fraction polynomial (GRFP) [3]. Both methods operate on the frequency response function (FRF) $\alpha_{j,k}(\omega)$ which in the form of a receptance function is the frequency domain ratio of displacement response at point *j*, $X_i(\omega)$, to forcing function at point *k*, $F_k(\omega)$, obtained via FFT of force and response time series.

Knowing mode shape ordinates ψ, all modal parameters can be extracted. The inertance FRF resulting from the data of Figure 4 is represented as the diamond data points in Figure 5 (left), and the smooth circle represents the best fit to the data. From the circle fit to the estimate of the modal constant which yields a modal mass of 55.5 tonnes.

6. Investigation on reliability of IMU data for force estimation

The first jumping experiment used an IMU on the sternum, although at that time it was not certain which would be the best position on the human body to capture the GRF with best accuracy. Hence a dedicated experimental campaign was conducted on a rigid laboratory floor to obtain a small database of directly measured GRFs and IMU data. Seven subjects aged 25 to 57 were tested: Two females and five males, weighing from 54 kg to 104 kg. Each subject was jumped for 20 second at each of nine frequencies from 1.5 to 2.1 Hz, in 0.1 Hz increments and at frequencies 2.25 Hz and 2.4 Hz corresponding to bridge mode frequencies. Each subject wore IMUs at C7, lower back (LB) and sternum (S). IMU and force plate signals were acquired separately and aligned in post-processing. FFT amplitudes of forces reconstructed based on data from IMUs and directly measured by the force plate were obtained and compared. The comparison for 43 usable jumping sequences is presented in Figure 5 (right).

The comparison only involves the fundamental component. In the figure the ratios are based on single Fourier lines. The evidence of Figure 5 (right) is clear: IMU data will slightly overestimate force (and hence mass) and data for single IMUs at either C7 or lower back signals could be used, with C7 preferable due to lower scatter.

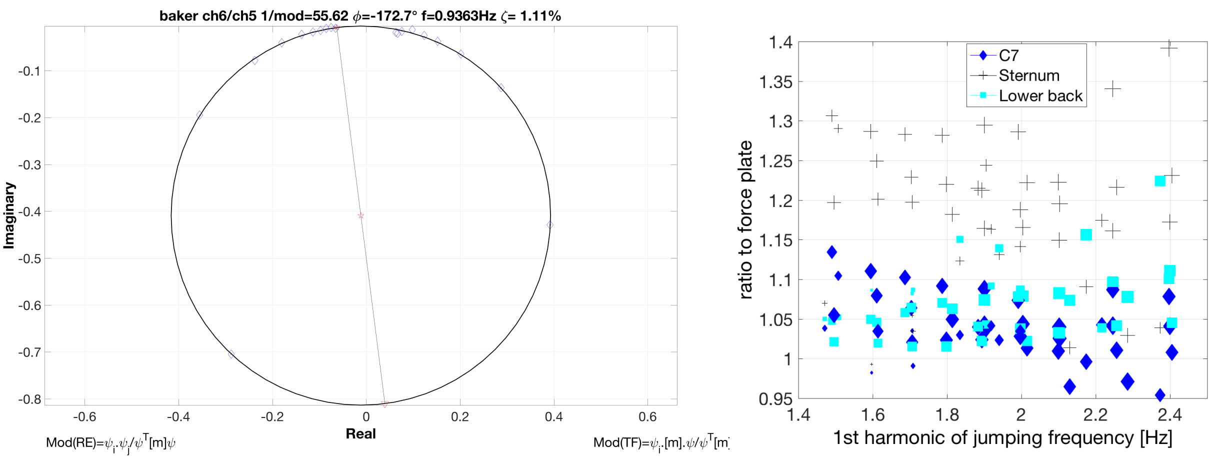

Figure 5: Left: FRF between acceleration response and jumping force reconstructed. m_n = 55.6 tonnes, f_n = 0.936 Hz.
Right: Reliability of IMU force data for first harmonic of jumping frequency.

7. Jumping tests using force plate and IMU at C7 vertebrae

Given the reliability of the C7 IMU data, further measurements were made on the bridge using including C7 and also using a long time interval between jumping sequences to allow good frequency resolution. Also to provide a one-time direct check, an AMTI Optima force plate was taken to site, in June 2015. One set of six IMUs was set at TPs on the South end of the front span, and a second set was used to instrument 2^{nd} author with IMUs on right foot, lower back, sternum and navel using mounting straps and also with one attached to the C7 vertebra on the back of the neck using adhesive tape. All 11 IMUs were assembled into a single synchronous network. Figure 6 (left) shows the experimental setup used with IMUs shown circled in red in the figure. The force plate is located at the transverse centre of the bridge between TP4 and TP21 (Figure 2) that is an antinode of mode 3.

The data from the force plate were corrected for the self-mass inertia force using the bridge acceleration signal and compared with forces reconstructed from 'C7', 'Sternum' and 'Lower back' IMUs. Figure 6 (right) shows the comparison of GRF time histories measured directly using the 'force plate' with reconstructed values for sternum, lower back and C7 vertebra. GRFs reconstructed using sternum and lower back accelerations overestimate the directly measured force significantly during the impact phase of the jump, while reconstruction using acceleration from the C7 vertebra shows good agreement with the force plate data.

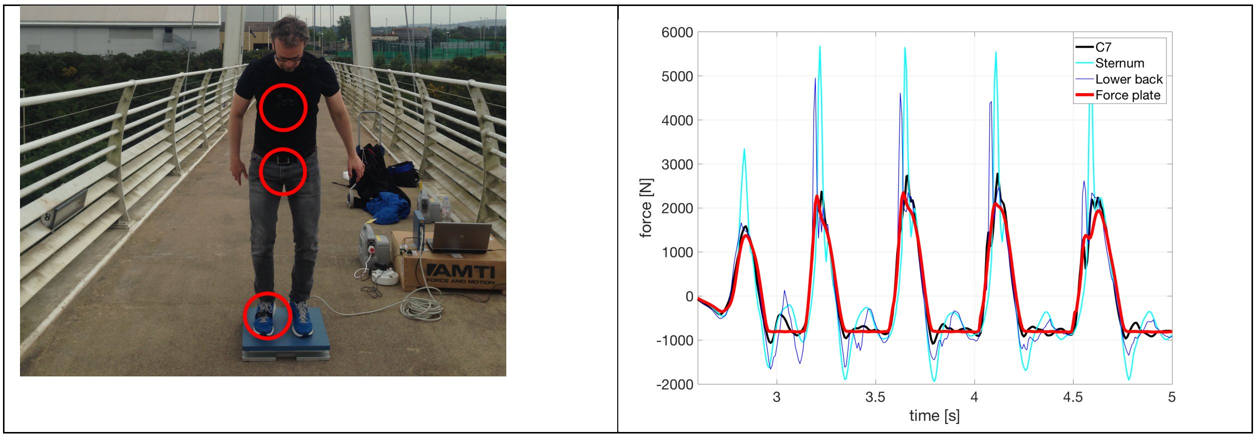

Figure 6: Left: Jumping test using IMUs at sternum, navel, lower back, C7 and right foot; the bridge is instrumented with IMUs and a force plate. Right: Jumping forces time history from force plate and IMUs for the second author jumping.

8. Application: Skybridges at National Gallery Singapore (NGS)

To show the real value of using IMUs alone for system identification two sets were taken to Singapore to investigate dynamic characteristics of a 'Skybridge' at NGS, shown in Figure 7. This spans a 21.2 m wide atrium between Singapore's former Supreme Court and City Hall buildings. It comprises two steel main chords supporting secondary steel cross beams, reinforced concrete on Bondek forming the deck, and Macalloy bar truss stiffening.

Figure 7: Skybridge at National Gallery, Singapore.

With the bridge fundamental frequency previously estimated as 4 Hz, jumping at 2 Hz was used to excite response via the second harmonic. Mode shapes were identified by IMU measurement of ambient vibrations and vibrations generated by jumping and walking activities. The frequency response function between C7 acceleration (proportional to jumping force) and bridge acceleration response is given in the form of the Nyquist plot of Figure 8 (left) for the lowest mode. To obtain modal mass requires scaling by the mass of the jumper and application of a correction factor such as shown in Figure 8 (right) for second harmonic frequency of jumping.

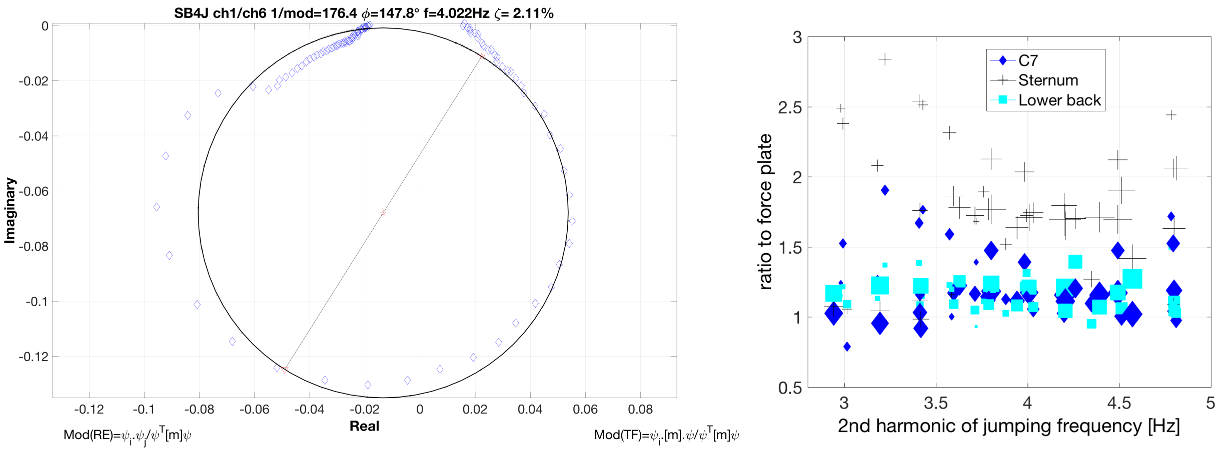

Figure 8: Left: Circle fit to mode 1 FRF using C7 vertical acceleration. Modal parameter estimates are: f_n= 4.022 Hz, ζ_n = 2.17 %. Right: Reliability of IMU force data for second harmonic of jumping frequency.

The modal mass estimate using the corrected force values is 12.3 tonnes, which agrees well with an estimate of 13.15 tonnes obtained using structural mass distribution according to measured mode shape.

9. Conclusions

The paper describes the use of inertial measurement units (IMUs) to identify ground reaction forces (GRFs) as well as for ambient vibration testing of footbridges in field conditions. All that is required is a set of compact wearable wireless sensors, with the C7 (neck) vertebra being the most suitable IMU location for estimating GRFs.

The methodology was demonstrated using data from a cable-stayed footbridge in Exeter having frequencies around the first harmonic frequency of jumping, and then for a simply supported footbridge in Singapore having natural frequency in the range of second harmonic frequencies of normal jumping.

The developed procedure could be useful for testing footbridges with modal frequencies in the range of the first and second harmonics of jumping and which are likely to suffer from vibration serviceability problems.

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