Embedded Data Processing in Wireless Sensor Networks for Structural Health Monitoring

N. DE BATTISTA, J. A. RICE, S.-H. SIM,
J. M. W. BROWNJOHN and H.-P. TAN

ABSTRACT

Eight wireless accelerometer sensor nodes (Imote2) equipped with energy harvesting solar panels were deployed continuously on an operational pedestrian footbridge in Singapore for two weeks. Each node periodically processed vibration data using a novel embedded data processing algorithm, referred to as the Filtered Hilbert-Huang transform, which resulted in a data reduction of 96%. From the processed results which the nodes transmitted to the base station, it was possible to conclude that resonant response from pedestrian walking excitation led to increased vibration levels during peak usage times. The maximum recorded peak and RMS acceleration were 52mg and 35mg respectively, which are within the limits allowed by several major design guidelines. This wireless sensor network deployment demonstrated the potential of decentralised, embedded data processing for wireless medium- and long-term structural health monitoring of civil infrastructure.

INTRODUCTION

Wireless sensor networks (WSNs) are becoming an efficient and cost-effective solution to structural health monitoring (SHM) applications where the installation of data cables is prohibitively expensive or impossible. Besides doing away with data cables, WSNs offer the possibility of carrying out distributed, decentralised data processing. Rather than transmitting all the raw data back to a central computer for post-processing (as is done with wired sensor networks), the microcontroller that is

---

Nicky de Battista, The University of Sheffield, Deptartment of Civil and Structural Engineering, Sir Frederick Mappin Building, Mappin Street, Sheffield S1 3JD, U.K.
Jennifer A. Rice, University of Florida, Engineering School of Sustainable Infrastructure & Environment, Gainesville, FL 32611, USA.
Sung-Han Sim, Ulsan National Institute of Science and Technology (UNIST), School of Urban and Environmental Engineering, UNIST-gil 50, Ulsan 689-798, Republic of Korea.
James M. W. Brownjohn, University of Exeter, College of Engineering, Mathematics and Physical Sciences, North Park Road, Exeter EX4 4QF, U.K.
Hwee-Pink Tan, Agency for Science, Technology and Research (A*STAR), Institute for Infocomm Research (I2R), #21-01 Connexis South, 1 Fusionopolis W ay, Singapore.

present in every WSN node can be used to process the raw data and transmit to the base station only the required results. When used carefully, this has the advantage of reducing the amount of data being transmitted, with associated benefits in wireless communication reliability, power saving and data management.

The technique of decentralised, embedded data processing (EDP) has been demonstrated in the past, using various algorithms to carry out model identification [1,2] and to estimate structural parameters such as natural frequencies [3,4] and cable tension [5]. In general, WSN nodes periodically acquire data which are either processed individually on each node or within clusters of nodes. The individual nodes or cluster heads would then transmit the estimated results to the base station (also referred to as the gateway node or data sink) and discard the raw data.

This study presents the use of a novel algorithm, referred to as the Filtered Hilbert-Huang transform (FHHT), for carrying out EDP of dynamic data on WSNs. It is based on the Hilbert-Huang transform [6] with modal separation using a bandpass filtering approach [7], combined with the Random Decrement technique [8]. Deployed over a period of time, this EDP method can be used to track temporal variations in a structure's dynamic behaviour.

Following a brief overview of the FHHT algorithm, this paper describes a two-week WSN monitoring deployment on a footbridge in Singapore. Each sensor node periodically acquired vibration data, processed them using the embedded FHHT algorithm and transmitted the requested results to the gateway node. This automated monitoring provided some interesting information about the use and performance of the footbridge. The results helped to determine the cause of disturbing vibrations which had been reported by pedestrians using the bridge.

EMBEDDED DATA PROCESSING USING THE FILTERED HILBERT-HUANG TRANSFORM

The FHHT-based EDP method comprises the following steps:

Step 1 - Digital high-pass filtering of data to eliminate low-frequency noise. In this deployment, a 6th order Butterworth filter with a cutoff frequency of 1Hz was used.

Step 2 - Calculation of two signal properties at fixed intervals of the data. The user can choose from: peak / peak to peak acceleration, root mean squared (RMS) acceleration, peak / peak to peak dynamic displacement, and R factor (RMS of the frequency-weighted acceleration divided by 0.005m/s^2, as per BS6841 [9]).

Step 3 - Mode separation by digital bandpass filtering (one filter per mode of interest). After inspecting the frequency content of a sample signal collected before monitoring, each filter's pass-band is set to retain a single vibration mode of interest, while allowing for any possible shift in natural frequency over time.

Step 4 - The Empirical Mode Decomposition [10] is applied to the filtered mode signals in turn to make them 'monocomponents'. Each monocomponent is effectively an estimate of that particular vibration mode's contribution to the signal. The modal RMS acceleration is estimated from the RMS of the monocomponent.

Step 5 - The Random Decrement technique [8] is used to estimate the free decay of each monocomponent in segments. The modal damping ratio of each segment is estimated from the logarithmic decrement of the segment's free decay.

Step 6 - The Hilbert transform [11] is applied to each monocomponent to obtain its complex analytic signal, from which the quasi-instantaneous natural frequencies [12] of each vibration mode of interest is estimated at regular intervals.

Step 4 followed by step 6 are commonly known as the Hilbert-Huang transform. In combination with the rest of the FHHT steps, the raw vibration data can be reduced to a few parameters pertaining to the overall signal (step 1) and to any number of its individual modes of vibration (amplitude in step 4, damping ratio in step 5, natural frequency in step 6), estimated at regular, closely-spaced intervals.

The FHHT algorithm was developed in such a way that it is implementable on low-power microcontrollers found on WSN platforms. A research collaboration was initiated between the authors in order to write the software as an add-on to the open-source ISHMP Toolsuite [13] and embed and test it on the Imote2 WSN platform.

STRUCTURAL HEALTH MONITORING USING EMBEDDED DATA PROCESSING

Following a series of verification lab tests, the FHHT method embedded on the Imote2 WSN platform was used to monitor the Labrador Park pedestrian overhead bridge (POB) in Singapore, for two weeks from 11th to 25th April 2013.

Labrador Park Pedestrian Overhead Bridge

The POB (Figure 1) is a seven-span footbridge located in the south of Singapore, linking the Labrador Park Mass Rapid Transit (MRT) station to the PSA building, which houses commercial outlets and offices. The four longer spans, referred to as T3 (33.66m span), T4 (31.61m span), T5 (26.17m span) and T6 (28.44m span), cross the northbound and southbound lanes of Alexandra Road and the eastbound and westbound lanes of Telok Blangah Road, respectively. T5 and T6 pass under the West Coast Highway, which runs parallel to Telok Blangah Road.

Each span comprises a simply-supported, structural steel, square hollow section truss. The bridge deck consists of a composite concrete slab cast on permanent steel formwork which is anchored to the trusses' top chords. The deck is shaded by a steel purlin and decking roof supported by steel circular hollow section columns.

The Land Transport Authority (LTA, Singapore) received a number of public complaints about disturbing levels of vibration being felt by pedestrians using the POB, particularly on spans T3 and T6. An independent study which was carried out in May 2012 on these two spans, using wired accelerometers and strain gauges,

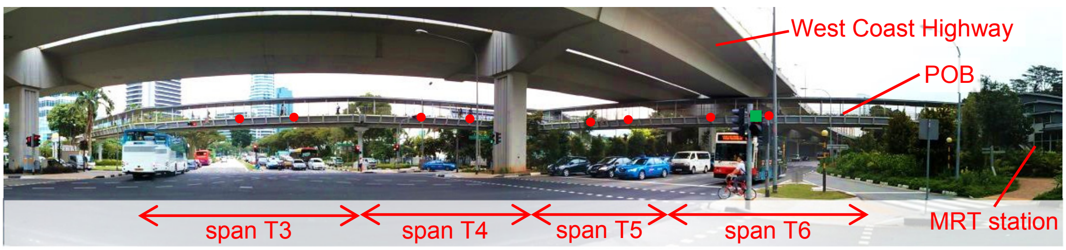

Figure 1. The Labrador Park pedestrian overhead bridge (POB) in Singapore. The red circles and green square indicate the approximate locations of the 8 remote and 1 gateway nodes respectively.

concluded that the main cause of vibration was due to pedestrian traffic. It also found that the first vertical natural frequency of T3 was excitable in resonance by the first harmonic of pedestrian walking forces [14].

The aim of the present study was to monitor all of the four main spans (T3 to T6) over a period of time, in order to obtain further information about their daily vibration pattern and how this related to the dynamic properties of the bridge.

Wireless Sensor Network Deployment

The WSN deployed on the Labrador Park POB consisted of eight remote sensor nodes and one gateway node. The remote nodes were placed on the outer edge of the trusses (out of reach), at approximately the mid-span and quarter-span points of spans T3, T4, T5 and T6. The gateway node was placed close to the mid-span of T6 (shaded by the expressway above the POB).

Each remote node (Figure 2a) comprised an IPR2400 Imote2 wireless platform, an ISM400 accelerometer sensor board (formerly known as SHM-A), an IBB2400 battery board and a *Tenergy* 15.6Ah Li-Ion battery, which was recharged via an *Adafruit Industries* USB/DC/Solar Lithium Ion/Polymer charger (v.1.0). All the components were secured in an ABS plastic weatherproof enclosure which was mounted on the steel truss using a strong magnet. A *Voltaic Systems* 3.4W 6V solar panel was wired to the charging circuit in each node. Four of the remote nodes which were constantly exposed to direct sunlight were protected with an insulating polystyrene box with a reflective foil outer layer to prevent them from overheating (Figure 2b).

The gateway node (Figure 2c) consisted of an IPR2400 Imote2, an IBB2400 battery board and an IIB2400 interface board, connected with a USB cable to a *Samsung* NC110 netbook. A *Huawei* 3G / Wi-Fi modem was used to provide the netbook with internet access, both for remote control (using *TeamViewer*) and for automatic data transfer (using *Dropbox*). All the components were enclosed in a metal weatherproof enclosure provided by *Tritech Ltd*. A USB webcam attached to the underside of the footbridge roof captured images of the deck at 30s intervals. In order to increase the wireless signal strength, a *TP-Link* TL-ANT2408CL 2.4GHz 8dBi high-gain, omni-directional antenna was mounted on a magnetic base and connected to each remote and gateway node with a 1.5m coaxial cable.

FHHT monitoring events were programmed to occur every 30 minutes. Each event started with the remote nodes being woken up from their sleep state to have

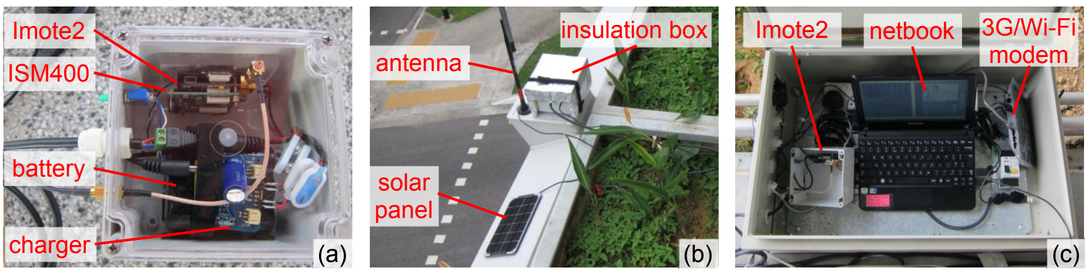

Figure 2. (a) An assembled remote node in a weatherproof enclosure; (b) a complete remote node installed on the footbridge; (c) the gateway node installed on the footbridge.

their battery levels checked and their clocks synchronised by the gateway node. The remote nodes then acquired 10 minutes of vibration data in the vertical direction at 100Hz sampling rate. Each remote node processed its own data with the specific FHHT filter and processing parameters it received from the gateway node. The results were transmitted to the gateway node, which staved them in a text file on the netbook. The remote nodes then went back into a low-power sleep state, waking up every 10s for 500ms to listen for transmissions from the gateway node.

Thus, ten minute snapshots of the performance of the monitored bridge spans were obtained every half an hour. These consisted of:

- peak and RMS acceleration calculated at 1s intervals, at mid- and quarter-spans (from 11th to 18th April);
- peak to peak dynamic displacement and R-factor calculated at 1s intervals, at mid- and quarter-spans (from 18th to 25th April);
- maximum RMS acceleration and natural frequency of the first (mid-span) and second (quarter-span) vertical modes of vibration, estimated at 1s intervals; and
- damping ratio of the first (mid-span) and second (quarter-span) vertical modes of vibration, estimated at 20s intervals.

The embedded FHHT processing reduced the 60000 data points acquired by each remote node during a monitoring event to just 2430 values. This represents a 96% reduction in the amount of data which needed to be transmitted wirelessly.

MONITORING RESULTS AND DISCUSSION

The signal parameters recorded throughout the monitoring exercise are shown in Figure 3. As expected, the overall daily maximum amplitudes of all the recorded parameters are higher on weekdays than on weekends, since the Labrador Park POB is used mostly by commuters walking between the MRT station and the nearby office buildings. The one-day average of the RMS acceleration recorded over the five weekdays of the first monitoring week (Figure 4) shows the daily usage pattern of the footbridge. The highest amplitudes were recorded during the morning rush hours (approximately 7:30am to 10:30am), followed by the evening rush hours (approximately 5:30pm to 9:00pm). A smaller increase in amplitude was also recorded during the lunch break hours (approximately 12:00noon to 3:00pm).

Table I shows the maximum values recorded from the four spans over the two-week monitoring period. The strongest sustained dynamic responses were recorded on span T3 (52mg peak, 35mg RMS), followed by T4 (48mg peak, 33mg RMS). Span T6 (52mg peak, 29mg RMS) also reached high levels of response but these were occasional and generally lasted for a short time.

According to the BD37/01 [15] guidance, the peak acceleration of T3 and T4 should not exceed 74mg. The British National Annex to Eurocode 1 [16] and the French Sétra footbridge design guidance [17] both limit the acceptable peak acceleration of the POB to 102mg for a mean comfort level. Following the Concrete Society's TR43 Appendix G [18], an upper limit of 128 on the R factor could be deemed reasonable for the POB. The vibration levels recorded on all four spans appear to be acceptable for human comfort, according to all of these documents.

The main reason behind the particularly strong vibration response of spans T3 and T4 is evident from the time-frequency plots in Figure 5. The first vertical

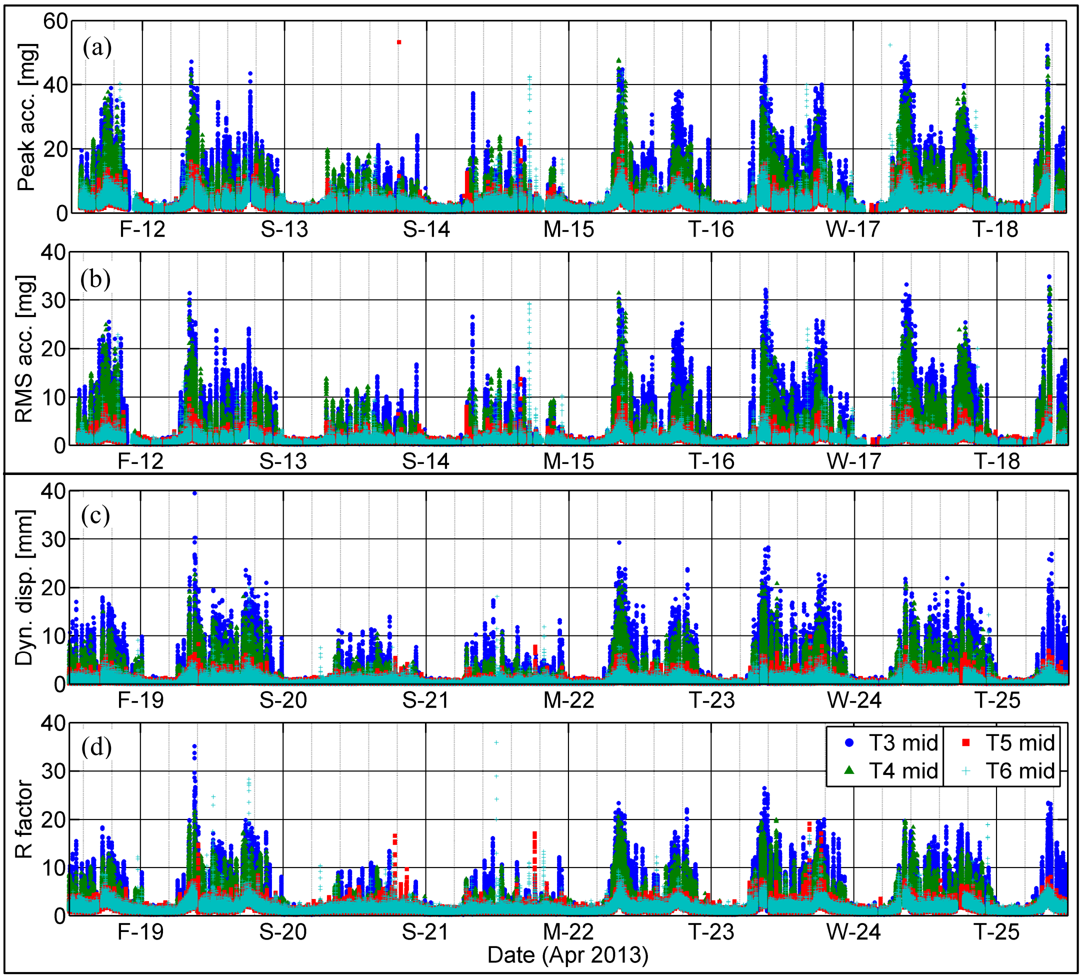

Figure 3. Signal parameters recorded during the two weeks of monitoring: a) peak acceleration, b) RMS acceleration, c) peak to peak dynamic displacements and d) R factors, calculated at 1s intervals from the mid-span acceleration data.

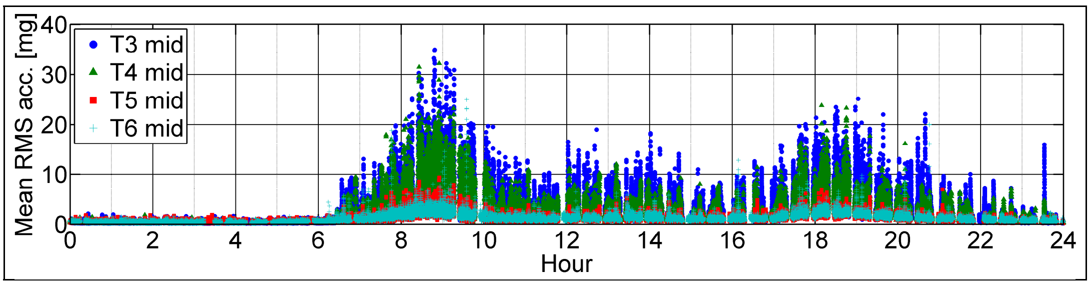

Figure 4. Mean of the RMS acceleration data acquired on weekdays between 11th and 18th April.

TABLE I. MAXIMUM SIGNAL PARAMETERS RECORDED AT MID-SPAN.

Span:	**T3**	**T4**	**T5**	**T6**
Peak acceleration [mg]	52	48	22 *	52
RMS acceleration [mg]	35	33	14	29
Dynamic displacement (peak to peak) [mm]	39	23	10	20
Frequency-weighted R factor	35	22	19	36

* Value of 53mg recorded on 13th April at 19:20:35 is excluded at it appears to be an isolated outlier.

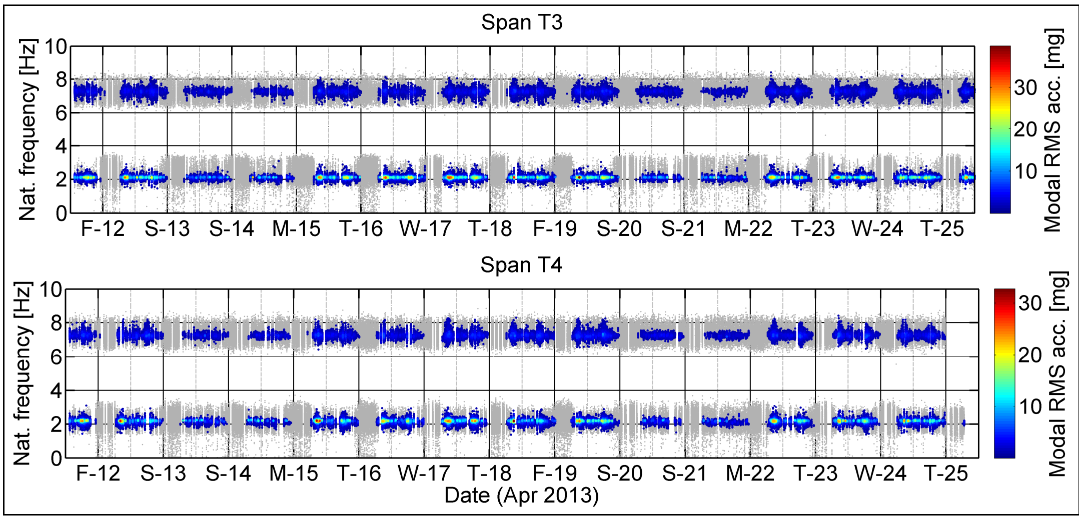

Figure 5. Natural frequencies of the first two vertical modes of vibration, estimated at 1s intervals with the embedded FHHT algorithm, for spans T3 (top) and T4 (bottom). For low energy vibration (modal RMS acceleration < 1mg), the frequency estimate is not reliable (shown in grey).

natural frequency of these two spans was found to be approximately 2.13Hz and did not appear to vary significantly over time. This falls within the range of normal walking pacing rates. Therefore the first mode of these two spans is susceptible to resonant excitation from human walking. As can be seen from the colour coding in Figure 5, the first vertical vibration mode dominated the overall response of spans T3 and T4. The first vertical natural frequency of span T5 was also approximately 2.13Hz. However, since it is shorter than T3 and T4, the vibration levels attained on T5 were consistently lower. In the case of T6, the first vertical natural frequency was approximately 2.59Hz, which is slightly higher than the normal walking pacing rates. Therefore it is likely that T6 exhibits mostly off-resonant response, with sudden increases in amplitude corresponding to occasional fast walking speeds.

CONCLUSION

A novel method for carrying out embedded data processing (EDP) in wireless sensor networks (WSNs) has been presented in this paper. The algorithm, referred to as the Filtered Hilbert-Huang transform (FHHT), was embedded on eight Imote2 WSN nodes. They were used to monitor the four longer spans of the Labrador Park pedestrian overhead bridge (POB) in Singapore for two weeks. To the best of the authors' knowledge, this is the first time that the FHHT algorithm has been embedded on WSNs to carry out autonomous monitoring of civil infrastructure.

The FHHT results obtained from the wireless monitoring deployment showed that resonant vibration in the first vertical mode was responsible for the bulk of the response in the critical spans. Despite public complaints, the vibration response of the POB was within the limits specified in several major design guidelines.

FHHT-based EDP, as demonstrated in this study, is expected to be a useful tool for medium- and long-term wireless monitoring of the vibration performance and tracking of dynamic properties of structures.

ACKNOWLEDGEMENTS

The authors are grateful to Ang Wee Boon and Tritech Group Ltd (Singapore) for assisting with the WSN deployment and Chua Hiang Ping, Rama Venkta, LTA and SMRT (Singapore) for providing access to the Labrador Park POB. This research was funded by EPSRC grant EP/G061130/1 (University of Sheffield) and by the "Sense and Sense-abilities" program (I^2R). The main author is supported by the University of Sheffield and A*STAR under the joint ARAP scholarship scheme.

REFERENCES

1. Sim, S.-H., B.F. Spencer, M. Zhang and H. Xie. 2010. "Automated decentralized modal analysis using smart sensors," *Struct. Control & Health Monit.*, 17(8):872–894.
2. Dorvash, S. and S. N. Pakzad. 2012. "Stochastic iterative modal identification algorithm and application in wireless sensor networks," *Struct. Control & Health Monit.*, online Oct 10.
3. Feltrin, G., J. Meyer, R. Bischoff and M. Motavalli. 2010. "Long-term monitoring of cable stays with a wireless sensor network," *Struct. & Infrastruct. Eng.*, 6(5):535–548.
4. Lei, Y., W. A. Shen, Y. Song and Y. Wang. 2010. "Intelligent wireless sensors with application to the identification of structural modal parameters and steel cable forces: from the lab to the field," *Adv. in Civ. Eng.*, 2010:1–9.
5. Cho, S., C.-B. Yun and J. P. Lynch. 2010. "Smart wireless tension force monitoring system for stay cables," in *Proceedings of the 5th International Conference on Bridge Maintenance, Safety and Management (IABMAS)*. Philadelphia, PA, USA, pp. 152–159.
6. Huang, N. E. and S. S. P. Shen. 2005. *Hilbert-Huang transform and its applications*. World Scientific Publishing.
7. Yang, J. N., Y. Lei, S. Pan and N. E. Huang. 2003. "System identification of linear structures based on Hilbert-Huang spectral analysis. Part 1: normal modes," *Earthq. Eng. & Struct. Dyn.*, 32(9):1443–1467.
8. Asmussen, J. C., S. R. Ibrahim and R. Brincker. 1998. "Random decrement: Identification of structures subjected to ambient excitation," in *Proceedings of the 16th International Modal Analysis Conference (IMAC XVI)*. Santa Barbara, CA, USA: Society for Experimental Mechanics, pp. 914–921.
9. British Standards Institution. 1987. *BS 6841:1997. Guide to Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock*. BSI.
10. Huang, N. E., Z. Shen, S. R. Long, M. C. Wu, H. H. Shih, Q. Zheng, N. C. Yen, C. C. Tung and H. H. Liu. 1998. "The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis," *Proc. of the Royal Soc. A: Math., Phys. & Eng. Sci.*, 454(1971):903–995.
11. Bendat, J. S. and A. G. Piersol. 2010. *The Hilbert transform. Random Data: Analysis and Measurement Procedures*. 4th ed. John Wiley and Sons, pp. 473–503.
12. Huang, N. E., Z. Wu, S. R. Long, K. C. Arnold, X. Chen and K. Blank. 2009. "On instantaneous frequency," *Adv. in Adapt. Data Anal.*, 1(2):177–229.
13. Rice, J. A., K. Mechitov, S.-H. Sim, T. Nagayama, S. Jang, R. Kim, B. F. Spencer, G. Agha and Y. Fujino. 2010. "Flexible smart sensor framework for autonomous structural health monitoring," *Smart Struct. & Syst.*, 6(5-6):423–438.
14. Middleton, C. J., J. M. W. Brownjohn. 2012. *Final report: POB bridge - Modal testing*. Sheffield, UK. Report ref. FSDL/2012/P0096-1 (unpublished).
15. The Highways Agency. 2001. *BD37/01. Loads for highway bridges*.
16. British Standards Institution. 2008. *UK National Annex to BS EN 1991-2:2003. Eurocode 1. Actions on structures. Traffic loads on bridges*. BSI.
17. Sétra. 2006. *Technical guide. Footbridges. Assessment of vibrational behaviour of footbridges under pedestrian loading*. Sétra.
18. Concrete Society. 1994. *Technical report no. 43. Post-tensioned concrete floors. Design handbook*. 2nd ed.