WIRELESS STRUCTURAL MONITORING OF A MULTI-SPAN FOOTBRIDGE WITH DECENTRALISED EMBEDDED DATA PROCESSING

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ABSTRACT

A pedestrian footbridge in Singapore was monitored for two weeks with a network of eight wireless accelerometer sensor nodes (Imote2). The nodes acquired 10 minutes of vibration data in the vertical direction every half an hour, processed the data using a novel embedded data processing algorithm and transmitted only the required results to the on-site base station. The base station then transferred the results to an off-site repository via a 3G connection. The embedded data processing method, which is referred to as the Filtered Hilbert-Huang transform, resulted in a data reduction of 96%. The results obtained throughout the monitoring exercise indicate 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.

KEYWORDS

Wireless sensor network, Structural health monitoring, Embedded data processing, Hilbert-Huang transform, Vibration serviceability, Footbridge.

INTRODUCTION

Wireless sensor networks (WSNs) offer an efficient and cost-effective alternative for structural health monitoring (SHM) applications where the installation of data cables is prohibitively expensive or impossible. Whereas in wired sensor networks all the raw data is transferred to a central computer for post-processing, the microcontroller that is 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 decentralised embedded data processing (EDP) has the advantage of reducing the amount of data being transmitted and thereby reducing the energy used for wireless communication (besides converting the saved information from a lot of meaningless data into a few useful numbers). Various algorithms have been embedded on wireless sensor nodes in the past to carry out model identification (Sim et al. 2010; Dorvash and Pakzad 2012) and to estimate structural parameters such as natural frequencies (Feltrin et al. 2010; Y Lei et al. 2010) and cable tension (Cho et al. 2010) in a decentralised manner. In general, EDP entails the WSN nodes periodically acquiring data which are either processed individually on each node (independent EDP) or within clusters of nodes (coordinated EDP). 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. The present study describes the use of a novel EDP algorithm, referred to as the Filtered Hilbert-Huang transform (FHHT), for tracking a structure’s dynamic properties and response over a period of time with a WSN. The FHHT is based on the Hilbert-Huang transform (Huang and S. S. P. Shen 2005) with modal separation using a bandpass filtering approach (Yang et al. 2003), combined with the Random Decrement technique (Asmussen et al. 1998).
Following a brief overview of the FHHT algorithm, this paper presents a two-week deployment of a WSN to monitor a lively footbridge in Singapore. Each sensor node in the WSN 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 algorithm, which was developed in such a way that it can run on low-power microcontrollers found on WSN platforms, comprises the following steps:

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

**Step 2** - Calculation of two response parameters at fixed intervals, chosen from: peak, peak to peak and root mean squared (RMS) acceleration; peak and peak to peak dynamic displacement; and R factor (a serviceability parameter defined as the RMS of frequency-weighted acceleration divided by 0.005m/s² (British Standards Institution 1987)).

**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 (Huang et al. 1998) is applied to the filtered mode signals in turn to extract the first intrinsic mode function (IMF) from each one. Each IMF is an estimate of that particular vibration mode’s contribution to the total response. The modal RMS acceleration is estimated from the RMS of the IMF.

**Step 5** - The Random Decrement technique is used to estimate the free decay of each IMF 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 (Bendat and Piersol 2010) is applied to each IMF to obtain its complex analytic signal, from which the quasi-instantaneous natural frequencies (Huang et al. 2009) of each vibration mode of interest is estimated at regular intervals.

Using this procedure, the raw vibration data is reduced to a few parameters pertaining to the overall response (step 1) and to any number of its individual modes of vibration (amplitude, damping ratio and natural frequency in steps 4, 5 and 6 respectively), estimated at regular, closely-spaced intervals. As a result of a research collaboration between the authors of this paper, the FHHT algorithm was programmed in C and nesC as an add-on to the open-source ISHMP Toolsuite (Rice et al. 2010) and embedded and tested 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) 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. It links the Labrador Park underground 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.

![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.](image-url)
Following the commissioning of the footbridge, 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, concluded that the first vertical vibration mode of T3 was susceptible to resonant excitation by the first harmonic of pedestrian walking forces (Middleton and Brownjohn 2012).

The aim of the present study was to monitor all four main spans (T3 to T6) in order to obtain a more holistic picture of the POB’s daily vibration pattern and to investigate 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 in a star topology (sing-hop network). 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, as indicated in Figure 1. 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) and an IBB2400 battery board. Power was supplied from a Tenergy 15.6Ah Li-Ion rechargeable battery connected to an Adafruit Industries USB/DC/Solar Lithium Ion/Polymer charger (v.1.0). A Voltic Systems 3.4W 6V solar panel was used to recharge the battery. The circuit boards and the battery were secured in an ABS plastic weatherproof enclosure which was mounted on the steel truss using a strong magnet. The four remote nodes on spans T3 and T4 were constantly exposed to direct sunlight during the day and were therefore covered by an insulating polystyrene box with a reflective foil outer layer to prevent them from overheating (Figure 2b). Despite positioning the solar panels to maximise their exposure to direct sunlight, the panels of two nodes (T5 quarter-span and T6 mid-span) were shaded for most of the time by the overhead Highway, thus supplying insufficient charge. The batteries in these two nodes were depleted and had to be replaced after 8 days. Out of the batteries in other nodes, three lasted for the entire 14 days and the other three lasted for 13, 13.5 and 13.75 days.

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 (Figure 2d). A Huawei 3G / Wi-Fi modem was used to make the netbook accessible via the internet for remote control (using TeamViewer) and for automatic data transfer (using Dropbox). All the components were locked in a metal weatherproof enclosure provided by Tritech Ltd. (Figure 2e). A USB webcam attached to the underside of the footbridge roof captured images of the deck at 30s intervals and stored them on the netbook. 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 (Figure 2b).

FHTT 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 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 a sampling rate of 100Hz and processed them with the FHTT filters and processing parameters sent by the gateway node. The results were then transmitted from each of the remote nodes in turn, to the gateway node which saved them in a text file on the netbook for automatic transfer to a cloud repository (Dropbox) via 3G connection. 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 bridge performance were obtained every half an hour. These consisted of:

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

By processing the raw data with the embedded FHTT algorithm, the 60000 raw data points acquired by each sensor node during a monitoring event were reduced to 2430 useful values, representing a data reduction of 96%.

![Figure 2. Components of the deployed WSN: (a) an assembled remote node in a weatherproof enclosure; (b) a complete remote node; (c) the gateway node; (d) screenshot of the gateway netbook; (e) the gateway enclosure.](image-url)
MONITORING RESULTS AND DISCUSSION

The time histories of the dynamic response parameters recorded throughout the monitoring period (Figure 3) show that the vibration levels of the footbridge were generally higher on weekdays than on weekends. This is to be expected since the Labrador Park POB is used mostly by commuters walking between the MRT station and the nearby office buildings. The average weekday usage pattern of the footbridge (Figure 4) indicates that 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). During the non-operation hours of the MRT (approximately midnight to 5:30am), the dynamic response was negligible (at sensor noise threshold level).

Vibration serviceability assessment

The maximum values of the response parameters recorded throughout the monitoring period are shown in Table 1. The strongest sustained acceleration responses were recorded on span T3 (52mg peak, 35mg RMS), followed by T4

![Figure 3. Response parameters recorded at 1s intervals at the mid-spans throughout the monitoring period: a) peak acceleration, b) RMS acceleration, c) peak to peak dynamic displacement and d) R factor.](image)

![Figure 4. One-day average of the RMS acceleration recorded on weekdays from 11th to 18th April.](image)

**Table 1. Maximum response parameters recorded at each mid-span (maximum overall is shown in bold).**

<table>
<thead>
<tr>
<th>Span:</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak acceleration [mg]</td>
<td><strong>52</strong></td>
<td>48</td>
<td>22 *</td>
<td><strong>52</strong></td>
</tr>
<tr>
<td>RMS acceleration [mg]</td>
<td><strong>35</strong></td>
<td>33</td>
<td>14</td>
<td>29</td>
</tr>
<tr>
<td>Dynamic displacement (peak to peak) [mm]</td>
<td><strong>39</strong></td>
<td>23</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Frequency-weighted R factor</td>
<td>35</td>
<td>22</td>
<td>19</td>
<td><strong>36</strong></td>
</tr>
</tbody>
</table>

* Value of 53mg recorded on 13th April at 19:20:35 identified as an isolated outlier and ignored.
(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. The maximum response of span T5 (22mg peak, 14mg RMS) was less than half that of the other spans.

According to the BD37/01 guidance (The Highways Agency 2001), the peak acceleration of T3 and T4 should not exceed 74mg. The British National Annex to Eurocode 1 (British Standards Institution 2008) and the French Sétra footbridge design guidance (Sétra 2006) both limit the acceptable peak acceleration of the POB to 102mg for a mean comfort level. Following the Concrete Society’s TR43 Appendix G (Concrete Society 1994), 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. Notwithstanding this, at the time of writing the LTA was still receiving complaints about disturbing levels of vibration being felt by the bridge users. As a result, a vibration mitigation solution was being investigated.

**Modal properties**

Figure 5 summarises the modal properties estimated by the embedded FHHT algorithm for the two livelier spans (T3 and T4). These plots show a time history of the quasi-instantaneous frequencies in relation to the vibration intensity of each mode. From the colour coding of the data points, it can be seen that the first vertical modes of these two spans dominate their overall vertical response. This is also the case for the other two spans, as shown in the frequency – amplitude plots in Figure 6.

A least squares linear best fit was estimated for all the modal frequency – amplitude sets (Figure 6). Data points having a modal RMS amplitude less than 2mg or a frequency falling outside their mode’s FHHT filter pass bands were excluded from the data sets. These points were considered to be coming from signals dominated by noise acquired at times when there was very little vibration.

From Figure 6 it can be seen that the estimated natural frequencies of all the spans have a nearly perfectly linear relationship with their corresponding modal amplitudes, indicating that the frequencies are not amplitude-dependent. The natural frequencies identified for each span (Table 2) are the y-axis intercepts of the linear fit lines.

The first vertical natural frequencies of spans T3 and T4 (2.11Hz and 2.15Hz respectively) fall well within the range of pacing frequencies for walking (often taken as being 1.5 – 2.5Hz). Evidently these two spans are easily excitable in resonance by walking pedestrians, leading to them being the livelier of the monitored spans. The first vertical natural frequency of span T5 (2.19Hz) is also excitable in resonance by walking. The lower level of response in this case is likely due to the shorter length of this span. As for span T6, the first natural frequency (2.57Hz) is slightly higher than normal walking pacing rates and therefore this span is more susceptible to off-resonant excitation. As a result, T6 generally experienced lower vibration levels than T3 and T4, with occasional high amplitude spikes probably coming from particularly fast walking or jogging.

The modal damping ratios estimated from the embedded FHHT algorithm are more complex to interpret and will be presented in future publications.

![Figure 5. Natural frequencies of the first two vertical vibration modes of spans T3 and T4. Grey points correspond to instances where the vibration energy was too low for a reliable frequency estimate (modal RMS acceleration < 1mg).](image-url)
CONCLUSION

The results of a two-week monitoring campaign on a multi-span footbridge in Singapore have been introduced in this paper. A wireless sensor network consisting of eight Imote2-based wireless sensor nodes and one gateway node was installed on the footbridge and set up to acquire and process vibration data autonomously. Each sensor node processed its acceleration data with a novel embedded data processing (EDP) method, referred to as the Filtered Hilbert-Huang transform (FHHT), thus reducing the amount of data by 96%. The processed results were transmitted wirelessly to the gateway node, stored on an on-site netbook computer and automatically copied to a cloud repository via a 3G connection.

The FHHT results obtained from the wireless monitoring deployment showed that the dynamic response of the critical spans was largely due to resonant vibration in their first vertical mode, the natural frequencies of which happen to lie within the range of normal walking pacing rates. The measured response of all the monitored spans was generally higher on weekdays, reaching a peak during the morning rush hours. Despite public complaints about disturbing levels of vibration being felt on the footbridge, the recorded dynamic responses were within the serviceability 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.

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