In-construction vibration monitoring of a super-tall structure using a long-range wireless sensing system

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Abstract

As a testbed for various structural health monitoring (SHM) technologies, a super-tall structure – the 610m-tall Guangzhou Television and Sightseeing Tower (GTST) in Southern China – is currently under construction. This study aims to explore state-of-the-art wireless sensing technologies for monitoring the ambient vibration of such a super-tall structure during construction. The very nature of wireless sensing frees the system from the need for extensive cabling and renders the system suitable for use on construction sites where conditions continuously change. On the other hand, unique technical hurdles exist when deploying wireless sensors in real-life structural monitoring applications. For example, the low-frequency and low-amplitude ambient vibration of the GTST poses significant challenges to sensor signal conditioning and digitization. Reliable wireless transmission over long distances is another technical challenge when utilized in such a super-tall structure. In this study, wireless sensing measurements are conducted at multiple heights of the GTST tower. Data transmission between a wireless sensing device installed at the upper levels of the tower and a base station located at the ground level (a distance that exceeds 443 m) is implemented. To verify the quality of the wireless

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measurements, the wireless data is compared with data collected by a conventional cable-based monitoring system. This preliminary study demonstrates that wireless sensing technologies have the capability of monitoring the low-amplitude and low-frequency ambient vibration of a super-tall and slender structure like the GTST.

Keywords: Wireless sensing; super-tall structure; ambient vibration; structural health monitoring (SHM); in-construction monitoring.

1. Introduction

The safety and reliability of our infrastructure systems are of crucial importance to human society. Natural and man-made hazards, as well as adverse operating conditions, may cause rapid deterioration to infrastructure systems such as buildings, bridges, and dams. To ensure infrastructure safety, future generations of intelligent civil structures are expected to have the ability of continuously monitoring the state of structural safety. Such intelligent structures should be instrumented with structural health monitoring (SHM) systems that are capable of accurately recording structural behavior during extreme loadings (*e.g.*, earthquakes, strong winds, heavy rains, etc.), providing information from which potential structural damage can be diagnosed, and issuing early warnings prior to structural failure [1-4]. In addition to preventing catastrophic structural collapse, the early damage detection provided by an SHM system can be highly valuable by enabling in-time and cost-effective structural maintenance.

An important functionality of an SHM system is to collect the signals from sensors installed on the structure and to store the measurement data in a central data logger. Traditionally, coaxial wires are employed for reliable data collection from sensors to the data acquisition system. However, the installation of coaxial wires in large civil structures can be expensive and labor-intensive. As modern infrastructure systems are generally large-scale and highly complex, the construction and maintenance of traditional cable-based SHMs can be extremely costly and time-consuming. To significantly reduce the cost while simultaneously offering the flexibility to relocate sensors, wireless communication technologies can be explored as an alternative to traditional tethered communication. Straser & Kiremidjian [5] explored the feasibility of integrating wireless radios with accelerometers for SHM purposes. Over the past decade, a great amount of research investment has been dedicated to advancing wireless sensing technologies for SHM [6-10]. For example, a recent issue of this journal also reported on the application of wireless sensing technology to structural monitoring applications [11-13]. As the building block of a wireless sensing system, a wireless sensing node usually contains an analog-to-digital converter for digitizing sensor data, a low-power microcontroller (possibly with the assistance of external memory) for executing embedded instructions, and a wireless communication module for the transfer of data. The structural sensors can be either contained inside, or external to the wireless sensing node. In order to achieve comparable performance with traditional monitoring systems, the design of a wireless sensor needs to consider various criteria such as the resolution of analog-to-digital conversion, on-board memory size, wireless data transfer rate, wireless communication range, power consumption, among others. A detailed literature review on wireless SHM can be found in [14].

Although the validation of wireless SHM is often conducted in laboratory settings, field validations of a number of academic and commercial systems have been reported in the literature. For example, Lynch, *et al.* [8] validated the performance of a prototype wireless sensor on the Alamosa Canyon Bridge in southern New Mexico. Chung, *et al.* [15] monitored structural responses of a footbridge on the University of California-Irvine campus using wireless MEMS sensors. Furthermore, Kim, *et al.* [16] reported on a large-scale deployment of wireless accelerometers on the Golden Gate Bridge in San Francisco. Different from laboratory tests, more uncertainties usually exist in field tests due to the complexity of the structure, the long transmission distances required in the field, and the low vibration amplitude commonly observed during ambient excitations. The wireless sensor unit deployed in this study is based on a prototype designed by Wang, *et al*. [17-18]. The wireless sensing system has been tested extensively on many civil structures. For instance, the prototype wireless sensing system was validated at the Geumdang Bridge (Icheon, Korea) for measuring vertical accelerations of the bridge deck excited by a truck traveling across the bridge [19]. In another field application, velocity meters integrated with the same prototype wireless sensing system successfully provided velocity data from which the vibration mode shapes of a cable-stayed bridge in Taiwan could be accurately identified [20].

Although wireless SHM has been investigated for bridge monitoring, there has been a limited number of reports addressing the application of wireless sensing for monitoring super-tall structures or structures under construction. This study aims to explore the effectiveness of wireless sensing technologies for monitoring the ambient vibration of an in-construction super-tall structure. Wireless sensing is especially well suited for in-construction monitoring because the modularity of the monitoring system allows for reconfiguration when site conditions are modified or when the objectives of the monitoring system change. The Guangzhou Television and Sightseeing Tower (GTST), a super-tall structure with a structural height of 610 m (consisting of a 450 m main tower and a 160 m antennary mast) is selected for this study. Without requiring extensive cabling, instrumentation in the form of a wireless sensing system poses minimum difficulty for use on the highly dynamic GTST construction site. These benefits are especially pronounced for larger-scale structures, such as the GTST, where traditional data acquisition systems would require the installation of kilometers of coaxial and fiber optic cables [21]. On the other hand, significant technical challenges exist for wireless sensing in such a demanding field application. For example, long wireless transmission distances are required when monitoring such a large structure, especially if the complexity and transmission latencies of multi-hopping communication schemes are to be avoided. In addition, the characteristically low-frequency (as low as ~0.1 Hz) and low-amplitude ambient vibrations common in tall slender towers like the GTST demands a high performance accelerometer and associated sensor signal conditioning to be integrated with the wireless sensing system.

This paper addresses the ambient vibration monitoring of the GTST using a prototype wireless sensing system. The low-amplitude and low-frequency ambient vibrations of the GTST require the use of a high-performance accelerometer, as well as a custom-designed high-gain, low-noise signal conditioning module with the wireless sensing system. In order to wirelessly transmit sensor data from the tower top to a ground station, a proprietary long-range wireless transceiver with high-gain antennas is adopted.

For performance verification, the wireless data collected during ambient vibration monitoring of the GTST is compared with that collected by a conventional tethered monitoring system permanently installed in the structure. The paper concludes with a summary of the performance of the wireless monitoring system within the GTST structure and details future research directions that would enhance the performance of wireless sensors for other complex, large-scale monitoring applications.

2. The GTST and Criteria for Ambient Acceleration Measurement

2.1 Description of the structure

The GTST is located on the bank of the Pearl River, in Guangzhou City, China and is the world's tallest tower structure upon completion in 2010 (Figure 1). With a tube-in-tube structural system, both the inner and outer structures of the tower have elliptical horizontal sections. The inner structure is continuous and made of reinforced concrete, while the outer structure is constructed from 24 interconnected concrete-filled-tube (CFT) columns. As shown in Figure 1, the CFT columns forming the outer structure incline vertically and are horizontally connected by steel ring beams and braces. There are 37 floor diaphragms distributed along the tower's height that link the outer steel frame with the inner concrete tube system. Owing to the hyperbolic shape, the size of the outer ellipse varies with the tower height, which makes the tower body increasingly slender as a function of the tower height. The dimension of the outer ellipse decreases from 60 m × 80 m at the underground level (namely, 10 m below grade) to the minimum of 20.65 m × 27.5 m at the height of 280 m; after the 280 m elevation, the ellipse begins to increase and peaks at 40.5 m × 54 m at the top of the main tower (at the tower's 450 m elevation). Meanwhile, the inner concrete tube's ellipse maintains a constant dimension (14 m × 17 m) along the entire tower height. As a landmark structure of the Guangzhou skyline, the tower possesses both aesthetic attraction and mechanical complexity. A detailed description of the tower and its structural design can be found in [22-23].

In addition to its significant achievement in architectural and structural design, the GTST is designated as an international testbed for use in advancing SHM methods and associated technologies (*e.g.*, sensors, algorithms, *etc.*) [22-23]. The Hong Kong Polytechnic University is responsible for monitoring the structural health conditions of the tower both during construction and when in service (*i.e.*, post-construction). To monitor environmental conditions and to quantify the external load on the tower, a weather station, anemometers, and a seismograph are permanently installed in the GTST. To monitor the response of the tower, vibrating wire temperature sensors, fiber optic temperature gauges, vibrating-wire strain gauges, fiber optic strain gauges, accelerometers, GPS receivers, digital video cameras, and tiltmeters are all installed during construction. For durability assessment, a suite of corrosion sensors are embedded to monitor the corrosion condition of the reinforced concrete inner structure. In total, a diverse array of 276 sensors are permanently installed to monitor the tower during long-term service [22]. The non-optical sensor outputs are acquired by a wired data acquisition system that consists of five data acquisition sub-stations that are connected by an optical fiber network running the height of the tower. The optics-based sensors require an optical sensor interrogator installed in the tower.

2.2 Instrumentation for vibration measurement

Prior to the installation of instrumentation, a detailed finite element analysis was conducted for the GTST. The analysis shows that the first natural frequency of the tower is around 0.11 Hz; in addition, the second through the tenth natural frequencies are all well within 1 Hz [23]. The acceleration amplitude due to ambient excitation is estimated to be at the level of 0.001 m/s^2 which can make the sensor signal highly susceptible to electrical noise. In order to identify a commercial accelerometer that is capable of accurately capturing such a low-frequency and low-amplitude signal, extensive experimentation was conducted with various types of accelerometers available in the market. These experiments found that the vast majority of the commercially available accelerometers typically used in civil engineering applications failed to capture such low-frequency and low-amplitude acceleration signals [22]. After an exhaustive search, the Tokyo Sokushin AS-2000C accelerometer demonstrated an acceptable performance level and was hence adopted in this study [24]. The uni-axial AS-2000C accelerometer has a frequency range of 0 to 50 Hz. The measurement range is ±20 m/s^2 and the sensitivity is 0.125 $V/(m/s^2)$. The accelerometer also offers a low noise floor of 1 μV for the frequency span of 0.1 to 10 Hz (*i.e.*, the range of interest in this study). A simple ±15 V DC power supply is required to power the accelerometer, and the current consumption of the accelerometer is 5 mA.

In the testbed cable-based sensing system, a total of twenty accelerometers are currently deployed at eight different sections along the height of the tower [25]. All of the accelerometers are installed on the inner tube structure of the tower, some measuring vibration along the long-axis of the inner ellipse while some are installed to measure vibration along the short-axis. Each accelerometer is mounted on a steel angle bracket that is firmly attached to the shear wall of the inner structure, as illustrated in Figure 2(a). After installation, the sensors are locked in a steel box for protection. These accelerometers are connected to the tethered data acquisition system, as part of the testbed effort. Data collected by the wired system will serve for baseline comparison while validating the wireless sensing system.

3. Wireless Sensing System Specialized for Tower Applications

3.1 Description of the wireless sensing system

The academic wireless sensing prototype shown in Figure 3 is an integrated wireless monitoring system that supports real-time data acquisition for civil structural monitoring [17-18]. The design of this wireless system was especially oriented for SHM applications in large-scale civil structures. For this reason, this prototype wireless monitoring system is adopted for exploring the feasibility of wireless sensing technologies in the ambient vibration monitoring of the GTST.

The prototype wireless sensing system incorporates an integrated hardware and software design to implement a simple star topology wireless sensor network [26]. A wireless SHM system with a star-topology includes multiple wireless sensing units in the network and one base station coordinating the activities of the network. In the prototype implementation, the base station can be a computer connected with a compatible wireless transceiver through an RS-232 or USB serial communication port. Through the associated wireless transceiver, the base station can communicate with the wireless sensing units that are spatially distributed throughout the structure. The wireless sensing units are responsible for acquiring sensor output signals, analyzing data, and transferring data to the base station for storage and further data analysis. While each wireless sensor is capable of performing on-board computing using a wide host of algorithms [10, 19], this study will rely on the base station to process data after the data has been collected.

The design of the wireless sensing unit consists of three functional modules, *i.e.*, the sensing interface, the computational core, and the wireless transceiver. The sensing interface converts analog sensor signals into a digital format usable by the computational core. The main component of the sensor signal digitization module is a 4-channel, 16-bit analog-to-digital (A/D) converter (Texas Instruments ADS8341). Each wireless sensing unit can accommodate signals from up to four analog sensors (each can be different from the other). The 16-bit A/D resolution is sufficient for most applications in civil engineering. One requirement imposed by the ADS8341 A/D converter is that the sensor signal should be between 0 and 5 V. The highest sampling rate supported by this A/D converter is 100 kHz. The digitized sensor data is then transferred to the computational core through a high-speed serial peripheral interface (SPI) port. Besides a low-power 8-bit Atmel ATmega128 microcontroller, external static random access memory (SRAM) is integrated with the computational core to accommodate local data storage and analysis. Embedded software was developed for the ATmega128 microcontroller, in order to allow the microcontroller to effectively coordinate the various hardware components in the wireless sensing unit. An extensive algorithmic library has also been embedded in the computational core to perform data processing tasks such as modal analysis and damage detection, on the sensor node itself.

The wireless sensing unit is designed to be operable with two different wireless transceivers: 900MHz MaxStream 9XCite and 2.4GHz MaxStream 24XStream [27]. Pin-to-pin compatibility between these two wireless transceivers makes it possible for the two modules to share the same hardware connection in the wireless unit. This dual-transceiver support affords the wireless sensing unit the opportunity to be used in different regions around the world, and to have more flexibility in terms of data transfer rate, communication range, and power consumption. For example, although the 9XCite transceiver requires less power consumption, it can only be used in countries where the 900 MHz band is for free public usage, such as the U.S., Canada, Mexico, and South Korea. Because the 900 MHz band is not an open, unlicensed public band in Guangzhou, China, the 24XStream transceiver operating on the open 2.4 GHz is employed in this study.

3.2 Additional hardware requirements

Although the selected Tokyo Sokushin AS-2000C accelerometers have the ability to capture the tower vibration, the signal amplitude caused by the tower vibration is very low. For example, with a sensitivity of 0.125 V/(m/s^2), the accelerometer output signal has a peak amplitude of only 0.125 mV at a vibration amplitude of 0.001 m/s^2. This level of voltage amplitude is highly susceptible to circuit noise and very difficult to directly digitize using typical analog-to-digital (A/D) converters. In order to make the signal ready for A/D conversion, a special low-noise signal conditioning module was designed to amplify and filter the sensor signal prior to A/D conversion (Figure 4).

The amplification gain of the signal conditioning module can be easily adjusted to 2, 20, 200 or 2000, for improving the signal-to-noise ratio during the A/D conversion. In addition, anti-aliasing is an important procedure in signal conditioning since it prevents high frequency signals and noise from irreversibly contaminating the digital data samples. The filtering circuit consists of a high-pass resistor-capacitor (RC) filter with a cutoff frequency of 0.014 Hz and a low-pass 4^{th}-order Bessel filter with a selectable cutoff frequency of 25 Hz or 500 Hz. The phase shift of a Bessel filter varies linearly with frequency, which is equivalent to a constant time delay to the signal within the passband. This special property helps to maintain the waveform of the time-domain signal. In addition, the Bessel filter is 4^{th} order which provides sufficient steepness in the frequency response function; this is highly effective in eliminating high-frequency components after the upper cut-off frequency. To serve different applications, a push-button switch is designed for conveniently alternating between the two cutoff frequencies (*i.e.*, 25 or 500 Hz). Using the signal conditioning module, the mean value of the analog sensor signal can be shifted to 2.5 V which is ready for digitization by the A/D module of the wireless sensing unit (*i.e.*, 2.5 V falls at the mid-point of the accepted A/D voltage range of 0 to 5 V).

Although the 24XStream transceiver is claimed to have a communication range of 5 km line-of-sight, the effective communication range may vary depending on field conditions. For certain field conditions, there are generally two ways to increase the wireless transmission distance: boosting the transmit power and using high-gain antennas. Since the transmit power of the 24XStream transceiver is fixed at 50mW, the only option left is to use high-gain antennas with the radio. After a series of extensive tests, 7.0 dBi outdoor omni-directional antennas (Buffalo AirStation Pro WLE-HG-NDC, Figure 5) are chosen to be deployed with the wireless sensing units used in the GTST ambient vibration tests. Prior to deployment, experiments are conducted to assess the reliable communication range of the radio. These tests demonstrate that a pair of 24XStream transceivers each using a 7.0 dBi antenna can reliably stream real-time acceleration data over an open distance of 500 m. Accordingly, this long communication range does come at a price; the 24XStream transceiver has a relatively high power consumption. For example, the transceiver powered at 5 V consumes 150 mA of electrical current during transmission and 80 mA during reception [27].

It should be noted that multi-hopping using short-range wireless transceivers is an alternative approach to the use of long-range single-hop transmission (as used in this study). The two approaches have their benefits and detriments. Using multi-hopping, the requirement on each wireless sensing unit's transmission range can be lowered, which may eliminate the need for high-gain antennas and long-range transceivers. This approach, under perfect communication conditions (*i.e.*, 100% data delivery), is theoretically more energy-efficient than long-range single-hop transmissions. In addition, under scenarios where heavy metal obstruction cannot be penetrated by the wireless signal, multi-hopping through relay units can potentially circumvent such obstructions. On the other hand, reliable multi-hopping requires more complicated middleware implementation on the wireless sensing units, due to the complexity inherent to multi-hopping networks. By relaying data through multiple wireless sensing units, greater communication latency is expected; this can render real-time collection more challenging or even infeasible. Furthermore, all relaying nodes along the hopping path have to consume some amount of battery power for transmitting a single packet; this is particularly disadvantageous for the few sink nodes that are close to the server, as the sink nodes need to relay all packets going into and out from the server. Finally, when the reliability of each hop reduces (*i.e.*, the data delivery rate is no longer 100%), the need to retransmit data many times in the multi-hop network can make the multi-hop network *less* power efficient than the single-hop transmission network implemented using more powerful transceivers.

3.3 Hardware calibration

In this study, both the wireless and the wired system adopt the same type of Tokyo Sokushin AS-2000C accelerometers. However, considering that one objective of this study is to verify the precision of the prototype wireless system, the accelerometers and the associated wireless sensing units are calibrated before installation in the field. First, to calibrate the data acquisition precision and noise performance of the wireless sensing unit, a standard sinusoidal voltage signal at 0.1 Hz is generated by an Agilent 33220A function generator and input to the aforementioned signal conditioner. The signal conditioner is configured to utilize 2000 times amplification and to use an anti-aliasing low-pass corner frequency of 25 Hz. The output from the signal conditioner is split with one output connected to a wireless sensing unit and the other to a National Instruments USB-6009 Data Acquisition (DAQ) unit which has a 14-bit A/D conversion resolution. Data acquisition results are depicted in Figure 6, which shows that while using the same conditioner, data acquisition performance of the wireless unit is as good as the NI USB-6009 DAQ. More importantly, as shown in Figure 6, since the input signal has very low background noise, the result reveal the outstanding signal-to-noise ratio performance of the wireless sensing unit. Specifically, the wireless sensing unit A/D does not appear to add any unexpected noise (*e.g.*, quantization error) to the measurement results.

Furthermore, calibration using typical ambient vibration data is also conducted. In the experiment setup, ambient vibrations at the GTST are collected by Tokyo Sokushin AS-2000C accelerometers and input into the proposed signal conditioner. The analog output signal of the signal conditioner is split with one output connected to the wireless sensing unit and the other to the NI USB-6009 DAQ. Data acquisition results are shown in Figure 7; the measurement results of both the wireless system and the NI USB-6009 DAQ are compared to that of the GTST permanent wired data acquisition system. It is clearly observed that the power spectral density (PSD) spectrum of the signal sampled by the wireless unit has close similarity with that of the NI USB-6009 DAQ and the GTST permanent wired data acquisition system (see Figure 7 (d), (e) and (f)). However, it can also be seen that the time domain amplitude of the wireless unit and the NI USB-6009 DAQ are slightly higher than that of the wired system (see Figure 7 (a), (b) and (c)). The reason for this difference can be well attributed to the different signal conditioning hardware using in the wireless and the wired systems..

3.4 Deployment configuration of the wireless sensing system

As mentioned previously, a total of twenty Tokyo Sokushin AS-2000C accelerometers are currently installed on the tower as part of the wired SHM system. In order to validate the performance of the wireless sensing system, six of the twenty accelerometers are selected to serve as a baseline when validating the wireless sensing system. These six uni-axial accelerometers measure the ambient vibration of the tower along two-horizontal directions at three heights. The three heights are listed in Table 1 and illustrated in Figure 8(a). As shown in Figure 8(b), at each height, two uni-axial accelerometers (one in the X-direction and the other in the Y-direction) are selected. For performance validation of the wireless system, an additional accelerometer is fixed on top of each of these six wired accelerometers (Figure 2(b)) so as to ensure the sensors are perfectly collocated. The output signal of this additional accelerometer is then connected to a wireless sensing unit through the low-noise high-gain signal conditioning module (Figure 9). Simultaneously, the wired data acquisition system collects the baseline data. The base station of the wireless sensing system, which receives the acceleration data from the wireless sensing unit, was located in the GTST construction site office situated at the ground level (Figure 10). The base station consists of a laptop computer connected with a 24XStream transceiver. The direct distance from the base station to the wireless sensing unit is up to 443 m.

Table 1 Three heights at which wireless measurements are performed.

Height of the wireless accelerometers (m)	Wireless communication distance (m)	Tower Story
168	168	33rd
225.2	225.2	44th
443.6	443.6	86th

4. Vibration Measurement Results

Using the low-noise high-gain signal conditioning module, ambient vibration signals at different heights of the tower are collected by the AS-2000C accelerometer and acquired by the wireless and wired sensing system. A sampling frequency of 50 Hz was adopted by both systems. To reduce the effect caused by different signal conditioning hardware in the cabled system and the wireless system, a bandpass digital filter (0.05 ~ 5 Hz) is first applied to the data collected by both systems. The time history and power spectral density spectra of the different vibration data sets are shown in Figures 11 to 16. Specifically, the comparison between the wireless ambient vibration data and the wired data in the X-direction at 168-m, 225.2-m and 443.6m heights are shown in Figures 11, 12 and 13, respectively. Each figure plots acceleration data collected for an hour. The one-hour acceleration data is collected by the wireless sensing unit and transmitted in real-time to the server. Because the vertical axis of Figure 13 is set to the same scale as the other figures for clarity in illustrating the waveform, the wireless data appears to be reaching the maximum and minimum limits of the plot. The phenomenon is not due to overshooting or high noise in the wireless system, but rather because the signal amplitude of the wireless system is higher than that of the cabled system (which is also shown in Figure 7).

The figures show that the wireless sensing system successfully collected acceleration data at different heights of the tower, including the uppermost section of the tower (443.6 m). Although some wireless signals are mildly noisier compared with the wired ones, they illustrate very similar waveforms. This shows that the wireless system was able to measure the extremely low-amplitude ambient acceleration of the tower. The validity of the wireless data can be further illustrated using the power spectra densities shown from Figures 11 to 13. Compared with the wired data, a number of dominant peaks, including resonant frequencies of the tower, can be found at similar frequencies in the wireless data. Table 2 compares the resonant frequencies of the tower measured by the wired and wireless systems. The resonant frequencies of the tower simulated by the finite element analysis are also listed in the table. The '---' mark indicates that the corresponding resonant frequency cannot be identified or is not clearly shown due to spurious modes evident in the spectra. The table also illustrates that the resonant frequencies obtained from the prototype wireless monitoring system are very close to these obtained from the wired system. Both wireless and wired data have similar peak frequencies as predicted by the finite element analysis.

Table 2 Comparison between the resonant frequencies of the GTST (in the X-direction) collected by the wired and wireless systems.

Height	Resonant frequency (Hz)						
	Simulated	0.0995	0.1437	0.3429	0.4800	0.8543	1.000
168 m	Wireless	---	---	0.3662	0.4761	0.7935	0.9644
	Wired	0.09155	---	0.3662	0.4761	0.7935	0.9644
225.2 m	Wireless	---	---	0.3662	0.4761	---	0.9644
	Wired	---	---	0.3662	0.4761	---	0.9644
443.6 m	Wireless	0.0977	0.1404	0.3662	0.4761	0.7996	0.9705
	Wired	0.0977	0.1404	0.3662	0.4761	0.7996	0.9705

Similar comparisons are performed for vibration data in the Y-direction. Figures 14 to 16 show the wireless and wired Y-direction vibration signal measured at different heights of the tower. Similar to the results demonstrated with the X-direction data, the Y-direction wireless data at different heights closely match the wired data. Although noise levels appear to be high in the low frequency range where the ambient vibration signal is weak, both wireless and wired systems show similar frequency characteristics. As shown in Table 3, the difference between the resonant frequencies identified from the wired and wireless data is small. In general, a close agreement was found between the ambient vibration signals collected from the wireless sensing system and from the wired data acquisition system.

Table 3 Comparison between the resonant frequencies of the GTST (in the Y-direction) collected by the wired and wireless systems.

Height	Resonant frequency (Hz)						
	Simulated	0.0995	0.1437	0.3429	0.4800	0.8543	1.000
168 m	Wireless	---	---	0.3052	0.4272	0.7935	0.9644
	Wired	0.09155	---	---	0.4211	0.7935	0.9644
225.2 m	Wireless	---	0.1343	0.3662	0.4272	0.7935	0.9644
	Wired	---	0.1404	0.3662	0.4211	0.7935	0.9644
443.6 m	Wireless	0.0977	0.1404	---	0.4211	0.7935	0.9644
	Wired	---	0.1404	---	0.4211	0.7935	0.9644

Different measurement durations are explored to observe its effect on the power spectra density (PSD) results. Using the same X-direction ambient vibration data (measured at 225.2 m height) as presented in Figure 12, Figure 17 shows the effect of the test duration on the PSD results. PSDs computed from different 20-minute segments of the one-hour acceleration data are plotted, for both wireless data and wired data. As the time duration is prolonged, the amplitude of dominant peaks increases, corresponding to higher signal-to-noise ratio. It can be observed that, for both the wireless and wired data, the PSD plot of the last 20 minutes (from the 40^{th} to the 60^{th} minute) is most similar to the PSD plot of the complete one-hour data. The reason is that as shown in Figure 12, the vibration during the last 20 minutes is the strongest among the three 20-minute segments.

Similar results can be observed from the ambient vibration signals measured along the Y-direction at the top of the tower (443.6-m height), as shown in Figure 18. The one-hour acceleration data as presented in Figure 16 is used for the multiple-duration PSD analysis in Figure 18. Among the three 20-minute segments, the time segment between the 40th and the 60th minute contributes most significantly to the overall PSD of the one-hour data, because as shown in Figure 16, this time segment has the highest vibration amplitude. In addition, the Y-direction wireless spectra in Figure 17 are relatively clean compared with the X-direction wireless spectra in Figure 18, due to the higher signal amplitude for the Y-direction data (shown in Figure 12). Nevertheless, both Figures 17 and 18 both show that the wireless spectra are reasonably close to the wired spectra. The overall results clearly illustrate that the wireless sensing system with the low-noise high-gain signal conditioning module can reliably collect the ambient vibration signal of the TV tower at various heights.

5. Summary and Discussion

This paper describes the in-construction vibration monitoring of the GTST performed using a wireless sensing system specially-designed for applications in large-scale civil structures. With the present hardware setup, the wireless communication works properly at different heights of the tower, for a direct distance of up to 443 m. Although some wireless data is slightly noisier compared with the wired data, the wireless measurements can provide accurate resonant frequencies of the tower. More significant, it is demonstrated that wireless sensing technologies can be deployed reliably in monitoring the low-frequency (~0.1Hz) and low-amplitude (~0.001m/s^2) ambient vibration of super-tall structures such as the GTST.

As the measurements of this work were conducted during the tower construction, many challenges due to a harsh and ever changing work environment have been confronted and overcome. First, as shown in Figures 11 through 16, even though the wireless data is often as high-quality as the wired data, the wireless data appears to be more strongly influenced by environmental noise (as caused by construction activities) than the wired system. One reasonable explanation for this phenomenon is that the wired system has a more reliable electrical ground connection for the power supply and therefore better shielded (*i.e.*, isolated) from external noise. Therefore, a reduction in the environmental noise susceptibility of the signal conditioning and wireless sensing unit circuitry may be one avenue for further improvement in the system design.

Besides this preliminary application of wireless sensing technologies on monitoring the in-construction super-tall structure, future studies will be aimed towards simultaneously collecting acceleration measurements at different levels along the height of the tower. Using time-synchronized acceleration data, vibration mode shapes of the tower can be extracted. In addition, the flexibility of the wireless sensing system can be further illustrated by concentrating a larger number of wireless sensors at one section of the tower during each test. The mode shapes of different sections of the tower can be identified separately and stitched together through overlapping measurement points between neighboring sections. It is expected that with very little reconfiguration effort, the wireless system will be able to provide dense measurements and higher-resolution mode shapes than the twenty “fixed” accelerometers of the current wired system.

6 Acknowledgements

The work described in this paper was supported in part by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU 5263/08E) and partially by a grant from The Hong Kong Polytechnic University through the Development of Niche Areas Programme (Project No. 1-BB95). Partial support from following institutions is also acknowledged: (1) Ministry of Science and Technology of China (863 Program Project No. 2009AA04Z420); (2) Science, Industry, Trade and Information Technology Commission of Shenzhen Municipality (Project No. SG200810150050A); (3) US National Science Foundation grant number CMMI-0928095 (Program Manager: Dr. Shih-Chi Liu) awarded to Prof. Y. Wang of Georgia Institute of Technology. In addition, the authors would like to acknowledge the kind assistance with the field testing provided by Dr. H.F. Zhou, Mr. W.Y Liao and Mr. W.H. Chen.

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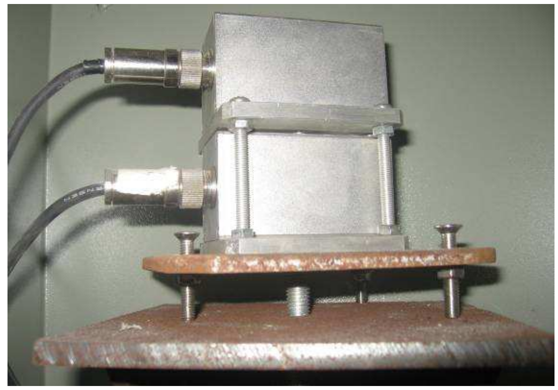
(a) July, 2007 (b) January, 2008 (c) January, 2009 (d) October, 2009

Figure 1. Guangzhou Television and Sightseeing Tower (GTST) at different construction stages

(a) Sensor setup of original wired system



(b) Sensor setup for simultaneous measurements by wireless and wired systems

Figure 2. Tokyo Sokushin AS-2000C accelerometers installed on a steel angle bracket that is fixed to the inner structure of the GTST

Figure 3. Wireless sensing prototype

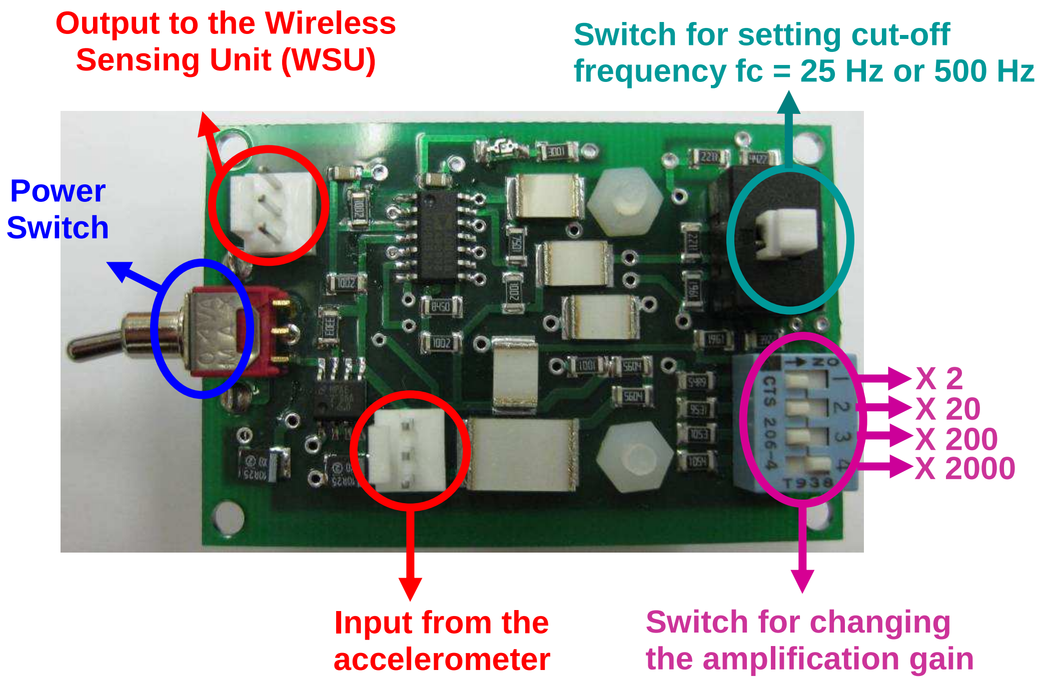


Figure 4. Low-noise high-gain (up to x2000) signal conditioning module

Figure 5. 7.0 dBi outdoor omni-directional antenna

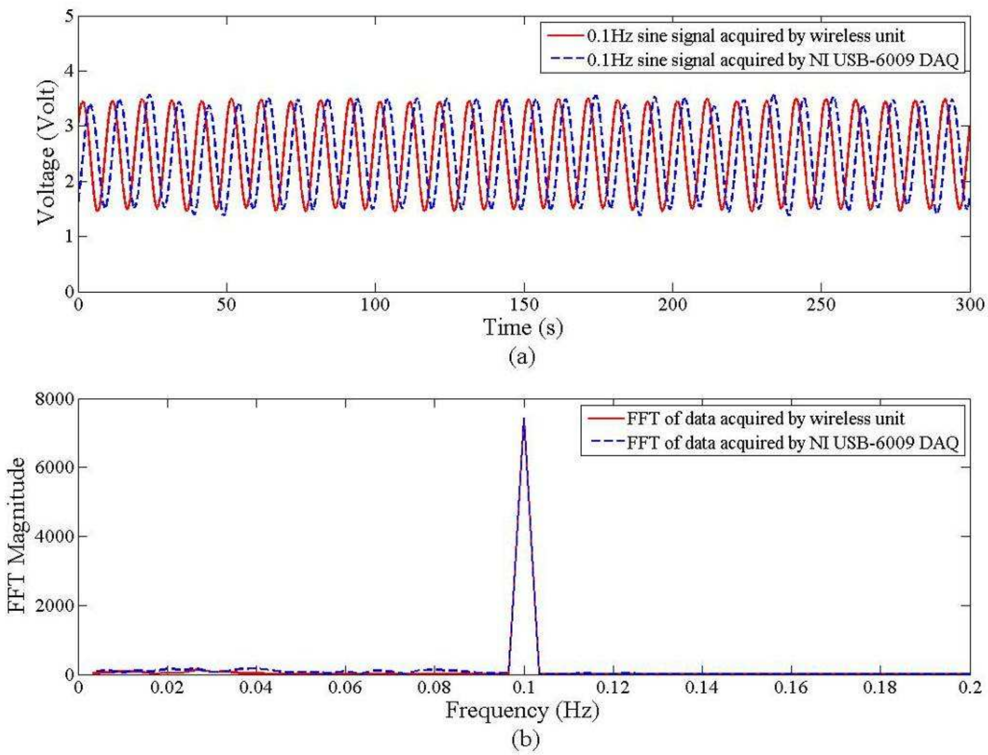


Figure 6. Wireless unit calibration using a standard sinusoidal signal generated by Agilent 33220A function generator: (a) Voltage data acquired by wireless unit and NI USB-6009 DAQ, (b) FFT magnitude

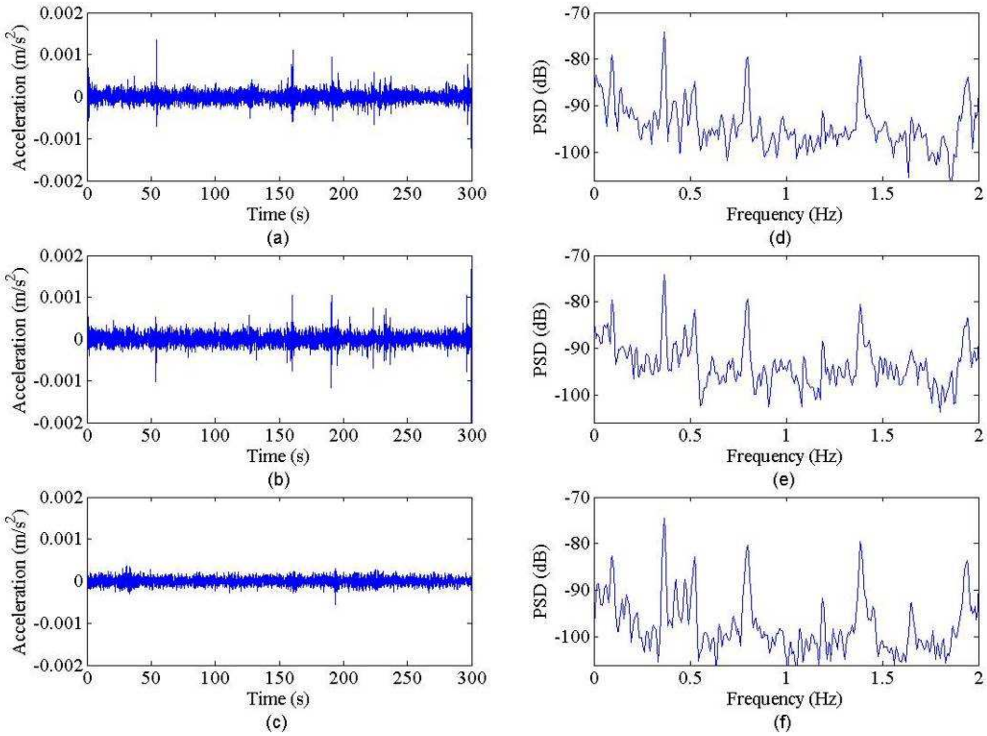
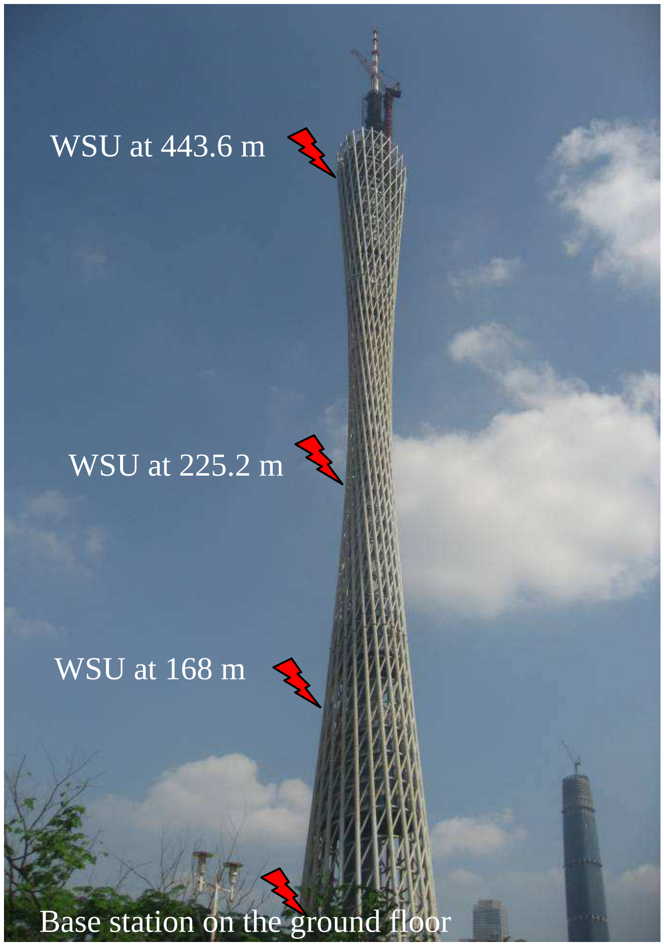
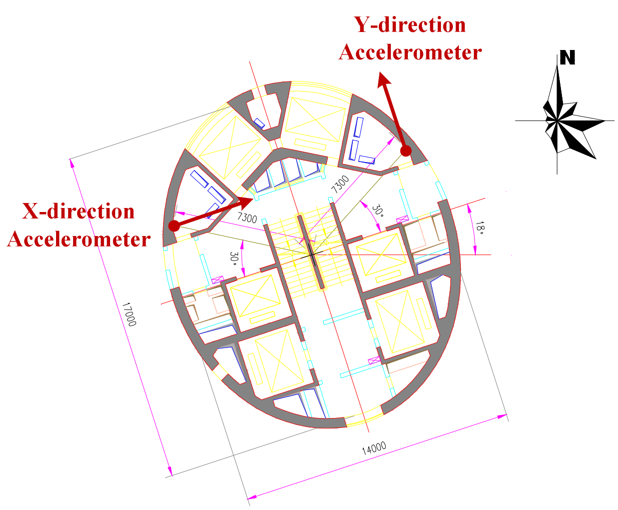


Figure 7. Wireless unit calibration using ambient vibration data of the GTST: (a) Acceleration acquired by wireless system, (b) Acceleration acquired by NI USB-6009 DAQ, (c) Acceleration acquired by wired system, (d) PSD of data acquired by wireless system, (e) PSD of data acquired by NI USB-6009 DAQ, (f) PSD of data acquired by wired system



(a) Three heights where measurements were taken [WSU: wireless sensing unit]



(b) Plan of the inner structure showing the locations of accelerometers

Figure 8. Experimental setup of wireless ambient vibration measurement at the GTST

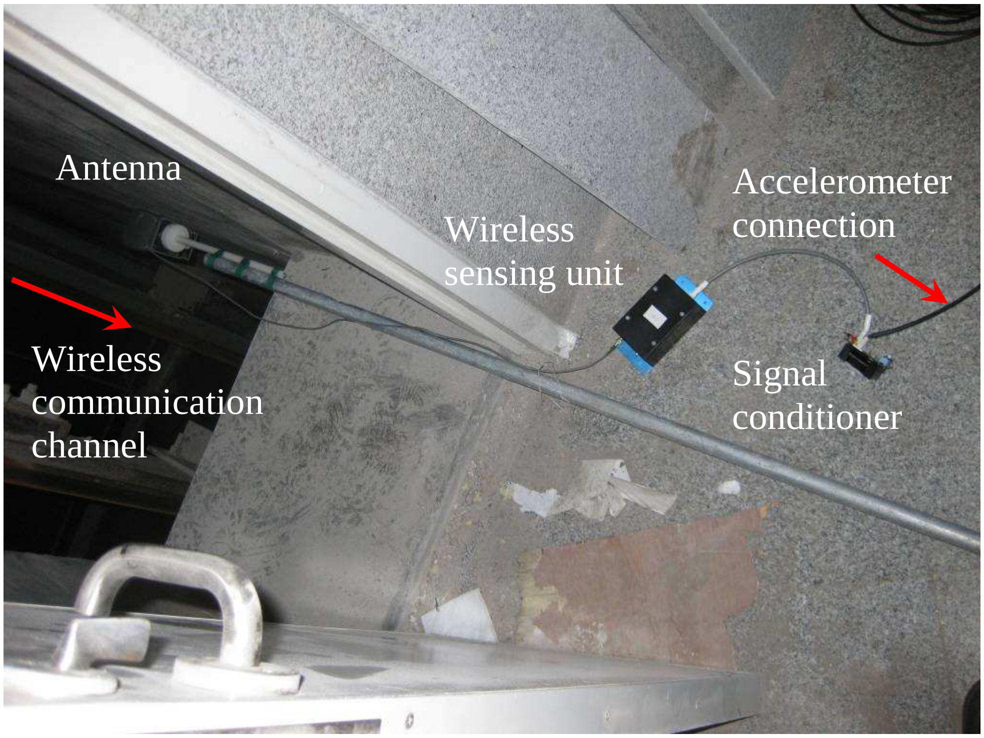


Figure 9. Experimental setup of the wireless sensing unit and the associated signal conditioning module inside the GTST

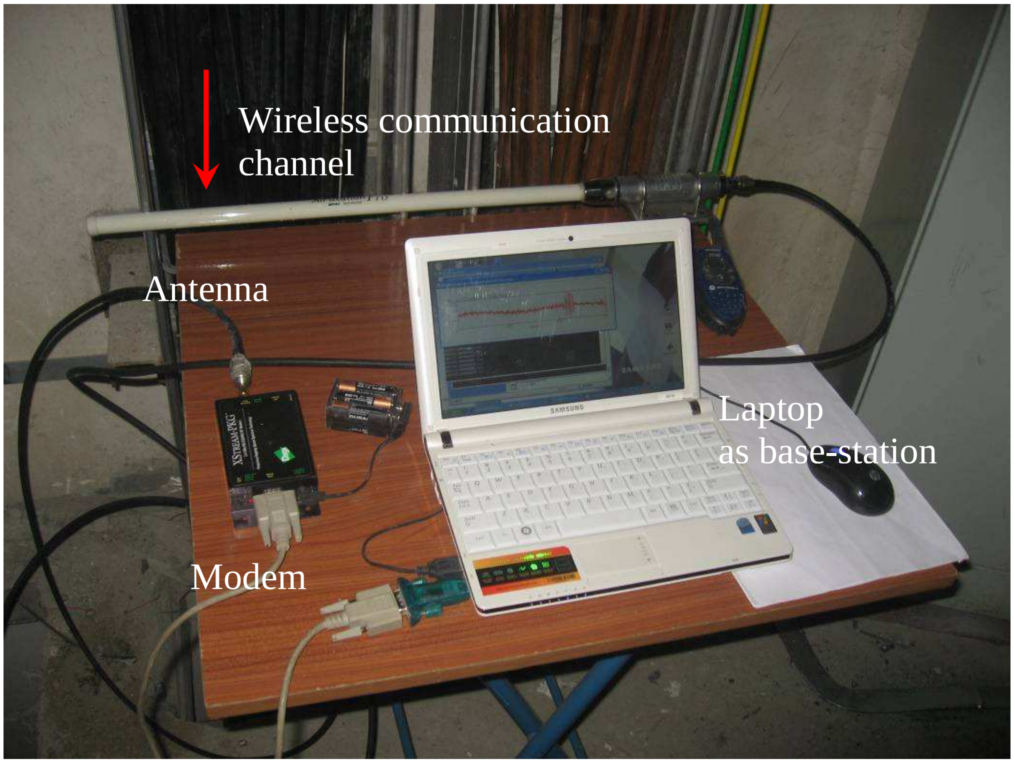


Figure 10. Experimental setup of the wireless base station at the site office on ground level

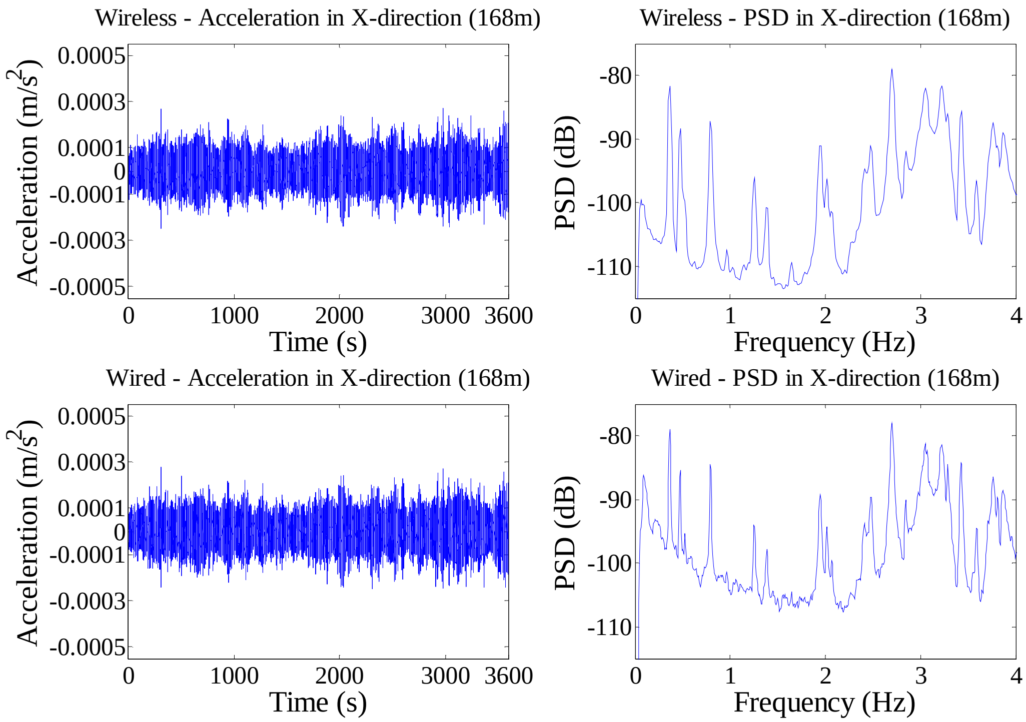


Figure 11. Ambient vibration signal of the GTST (Left: time history; Right: frequency domain) from an X-direction accelerometer at 168-m height received by the wireless sensing system (top) and the wired data acquisition system (bottom)

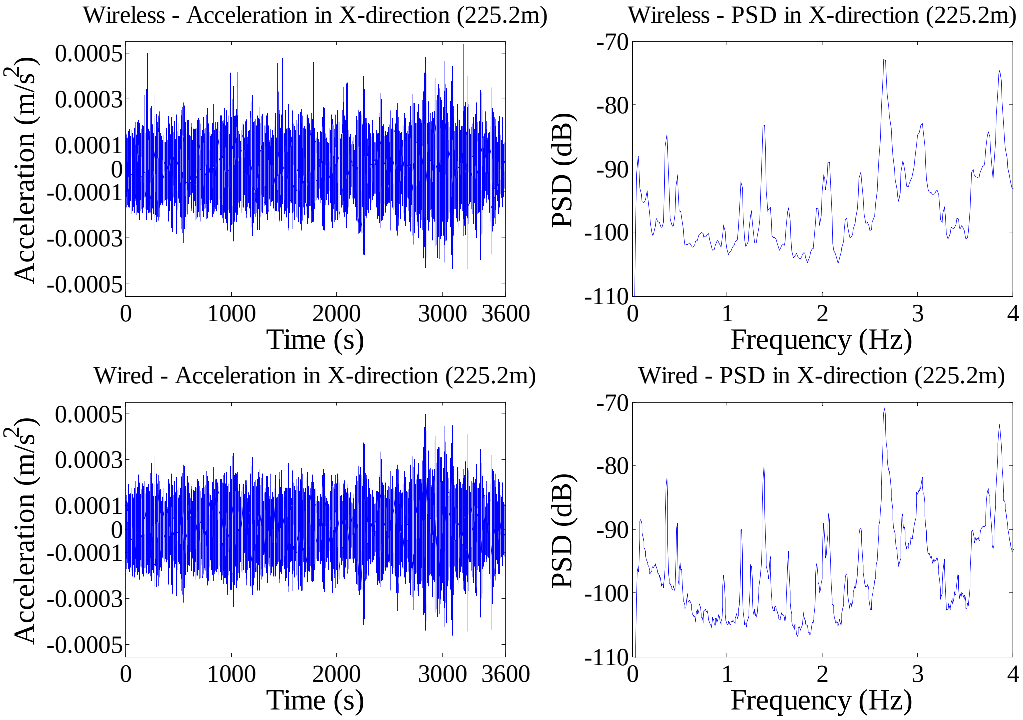


Figure 12. Ambient vibration signal of the GTST (Left: time history; Right: frequency domain) from an X-direction accelerometer at 225.2-m height received by the wireless sensing system (top) and the wired data acquisition system (bottom)

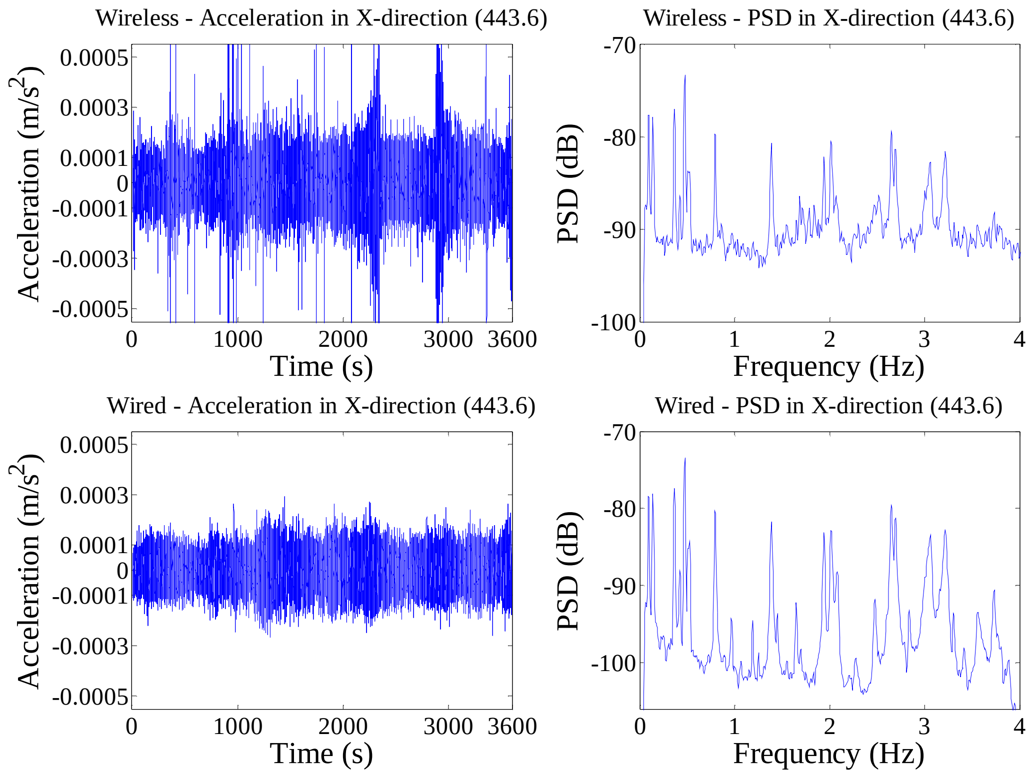


Figure 13. Ambient vibration signal of the GTST (Left: time history; Right: frequency domain) from an X-direction accelerometer at 443.6-m height received by the wireless sensing system (top) and the wired data acquisition system (bottom)

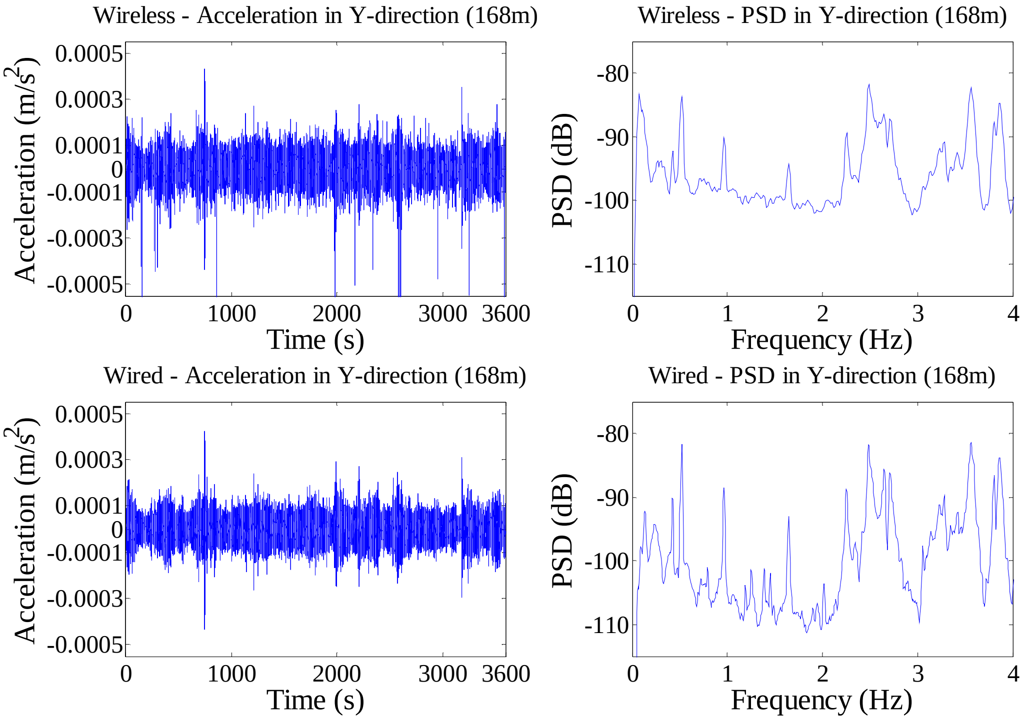


Figure 14. Ambient vibration signal of the GTST (Left: time history; Right: frequency domain) from a Y-direction accelerometer at 168-m height received by the wireless sensing system (top) and the wired data acquisition system (bottom)

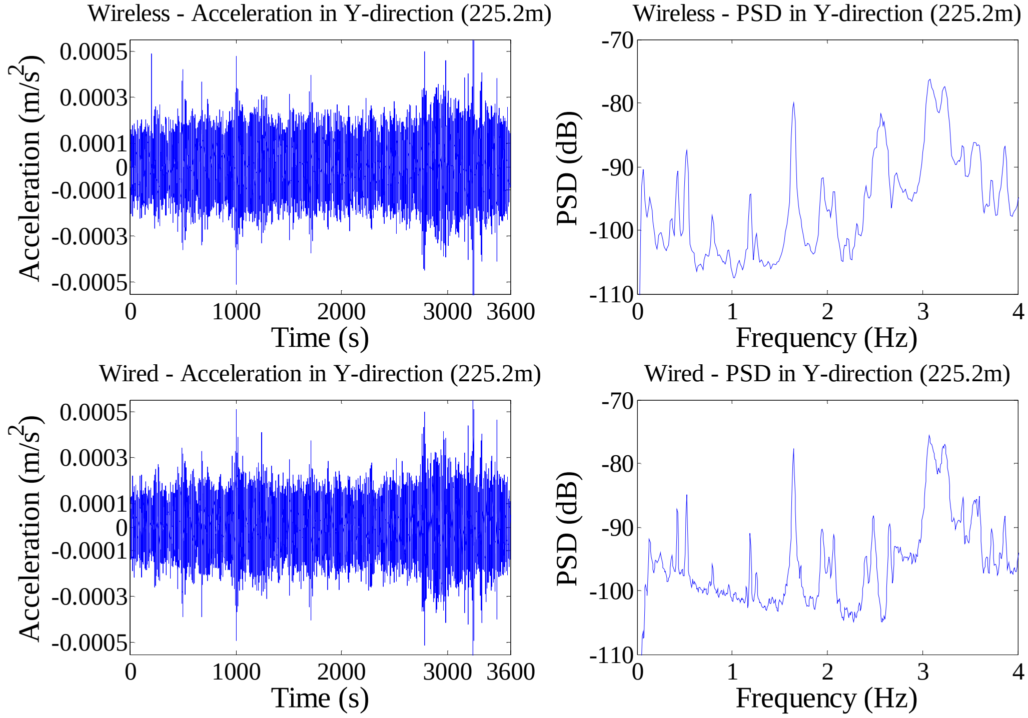


Figure 15. Ambient vibration signal of the GTST (Left: time history; Right: frequency domain) from a Y-direction accelerometer at 225.2-m height received by the wireless sensing system (top) and the wired data acquisition system (bottom)

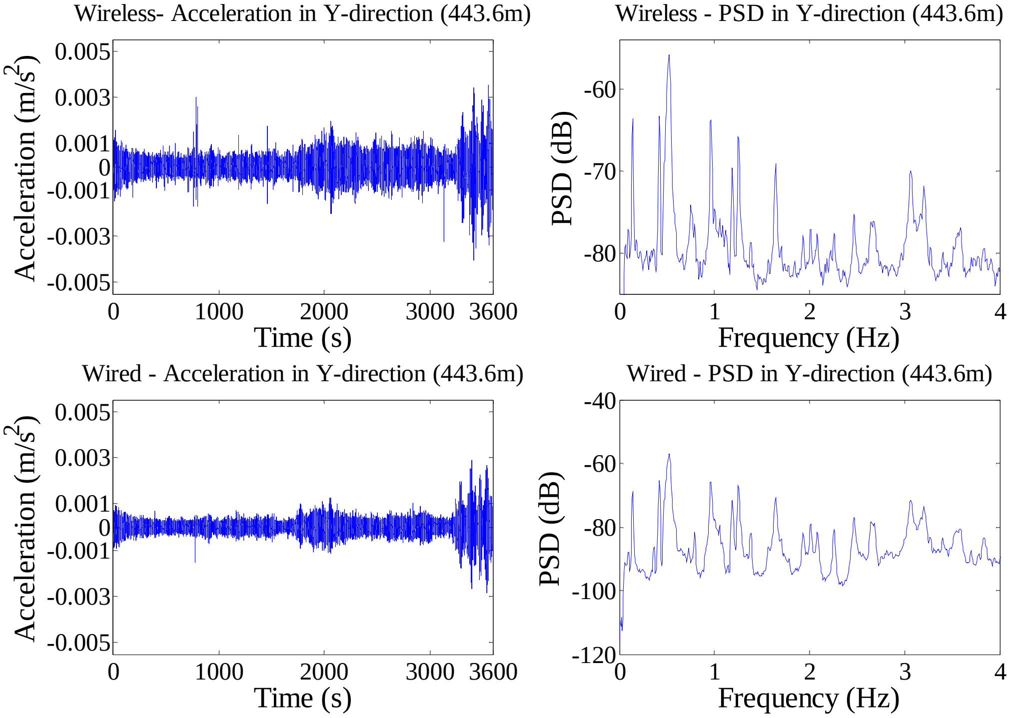


Figure 16. Ambient vibration signal of the GTST (Left: time history; Right: frequency domain) from a Y-direction accelerometer at 443.6-m height received by the wireless sensing system (top) and the wired data acquisition system (bottom)

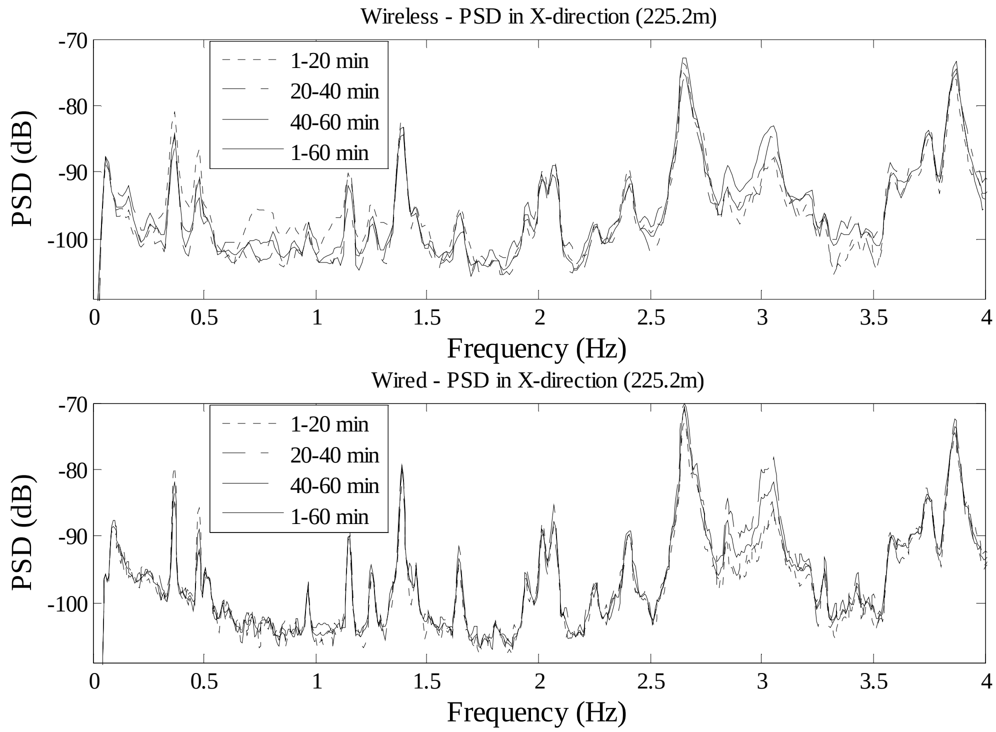


Figure 17. PSD performance of data within different segments of an hour (the data was collected by an X-direction accelerometer at 225.2-m height and simultaneously acquired by the wireless sensing system and the wired data acquisition system)

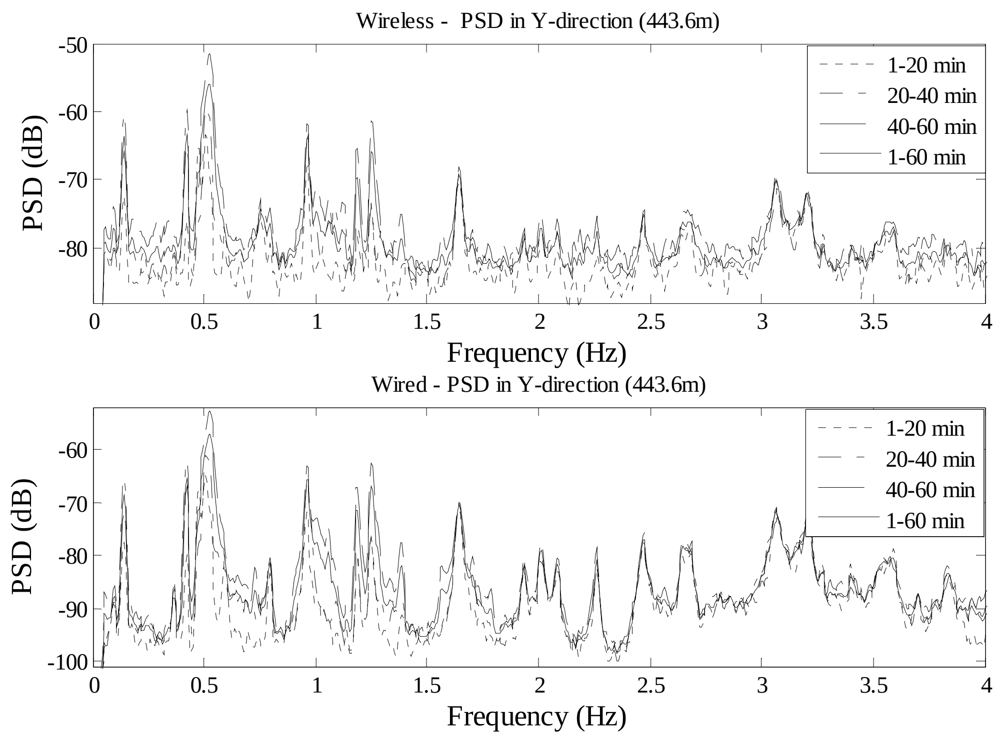


Figure 18. PSD performance of data within different segments of an hour (the data was collected by a Y-direction accelerometer at 443.6-m height and simultaneously acquired by the wireless sensing system and the wired data acquisition system)