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

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Abstract

As a testbed for various structural health monitoring (SHM) technologies, a supertall 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 an in-construction supertall structure. The nature of wireless sensing makes the system free of extensive cabling and most suitable for application to in-construction structures. On the other hand, unique difficulties exist in the field application. 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 a long distance is also challenging for the application to such a supertall structure. In this study, wireless sensing measurements are conducted at multiple heights of the tower. Data transmission is performed from the wireless sensing device to a base station located at the ground level, over a distance up to 443.6 m. To verify the quality of the wireless measurements, the wireless data is compared with data collected by a conventional cable-based monitoring system. This preliminary study demonstrates that wireless sensing

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technologies have the capability of monitoring the low-amplitude and low-frequency ambient vibration of an in-construction supertall structure.

Keywords: Wireless sensing; supertall 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 the 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 for diagnosing potential structural damage, 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 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 infrastructures are usually 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 and increase the flexibility of sensor relocation, 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. Over the past decade, a great amount of efforts have been dedicated by the research community in exploring wireless sensing technologies for SHM [6-10]. A recent issue of this journal also reported various applications of wireless sensing technologies [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) that executes embedded instructions, and a wireless communication module. 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, etc. 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. Kim et al. [16] reported 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, long transmission distance required in the field, low vibration amplitude from ambient excitations, etc. The wireless sensor unit deployed in this study is based on a prototype designed by Wang et al. [17-18]. The prototype wireless sensing system with up to 14 nodes was validated at the Geumdang Bridge located in Korea, for measuring the vertical vibration of the bridge deck excited by a truck traveling through the bridge [19]. In another field application, ten wireless velocity meters successfully provided velocity data for identifying the vibration mode shapes of a cable-stayed bridge in Taiwan [20].

Although wireless SHM has been investigated for bridge monitoring, there has been limited number of reports addressing the application of wireless sensing for monitoring supertall structures or in-construction structures. This study aims to explore the effectiveness of wireless sensing technologies for monitoring the ambient vibration of an in-construction supertall structure. The Guangzhou Television and Sightseeing Tower (GTST), a supertall structure with a structural height of 610-m (consisting of the 450-m main tower and the 160-m antennary mast), is selected for this study. Without requiring extensive cabling, instrumentation of a wireless sensing system poses minimum difficulty for an in-construction structure. Such benefit becomes more evident for larger-scale structures, such as the GTST, where traditional data acquisition systems can easily entail kilometers of co-axial and fiber optic cables [21]. On the other hand, significant challenges exist for such a field application. For example, long wireless transmission distances are desirable for the application to a supertall structure, particularly if the complexity and data transmission latency of a multi-hopping network is to be avoided. In addition, the low-frequency (as low as ~0.1 Hz) and low-amplitude ambient vibration of the GTST poses high requirement to the accelerometer selection and associated sensor signal conditioning design.

This paper addresses the ambient vibration monitoring of the GTST using a prototype wireless sensing system. The low-amplitude and low-frequency characteristics of the ambient vibration at the GTST entail a specially-selected accelerometer, as well as a specially-designed high-gain low-noise signal conditioning module. 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 is compared with that collected by a conventional tethered monitoring system.

2. The GTST and Criteria for Ambient Acceleration Measurement

2.1 Description of the structure

The GTST is located on the bank of 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 comprises 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 bracings, as well as 37 floor diaphragms at various heights. Owing to the hyperbolic shape, the outer ellipse varies with the tower height, which makes the tower body increasingly slender as the height rises. The dimension of the outer ellipse decreases from 60 m × 80 m at the underground level (-10 m height) to the minimum of 20.65 m × 27.5 m at the height of 280 m, and then increases to 40.5 m × 54 m at the top of the main tower (450m height). Meanwhile, the inner ellipse maintains a constant dimension (14m × 17m) along the tower height. As a landmark structure of the Guangzhou skyline, the tower possesses both aesthetic attraction and mechanical complexity. Detailed descriptions about the tower structure can be found in [22-23].

In addition to its significant achievement in architectural and structural design, the GTST is designated as a testbed for practice and research of SHM [22-23]. The Hong Kong Polytechnic University is responsible for monitoring the structural health conditions of the tower in both construction and service stages. To monitor environmental conditions and quantify external load, a weather station, a number of anemometers, and a seismograph, are deployed. 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 installed. For durability assessment, a suite of corrosion sensors are embedded to monitor the corrosion condition of the reinforced concrete inner structure. In total, 276 sensors of different types are used in the sensory system for long-term monitoring during the service stage [22]. Signals from most sensors are acquired by the wired data acquisition units located at five sub-stations connected by an optical fiber network. The optical sensor interrogator and the five data acquisition units, together with the local area networks and a global Ethernet network, constitute the complete data acquisition and transmission system.

2.2 Instrumentation for vibration measurement

Prior to sensor instrumentation, 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 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 low-amplitude signal, extensive experiments were conducted with various types of accelerometers available in the market. Our experiments found that the vast majority of commercially available accelerometers typically used in civil engineering failed to capture the waveforms of such a low-frequency and low-amplitude acceleration signal [22]. After an exhaustive search, the Tokyo Sokushin AS-2000C accelerometer demonstrated acceptable performance and was adopted in this study [24]. The uni-axial AS-2000C accelerometer has a frequency range of DC - 50 Hz. The measurement range is ± 20 m/s^2 and the sensitivity is 0.125 $V/(m/s^2)$. The accelerometer offers a low noise floor of 1 μV for the frequency span of 0.1 ~ 10 Hz. A simple ± 15 V DC power supply is required by the accelerometer, and the current consumption of the accelerometer is 5 mA.

In the testbed cable-based sensory system, a total of twenty accelerometers are currently deployed at eight different sections along the height of the tower [25]. All the accelerometers are installed on the inner structure of the tower, some measuring vibration along the long-axis of the inner ellipse, and some measuring 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. A Wireless Sensing System Specialized for the Tower Application

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 in civil structure monitoring [17-18]. The design of this wireless system was especially oriented for SHM applications in large-scale civil structures. This prototype system is adopted for exploring 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 RS-232 serial communication or USB communication. Through the associated wireless transceiver, the base station can communicate to the wireless sensing units that are allocated 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.

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 a heterogeneous set of up to four analog sensors. The 16-bit A/D resolution is sufficient for most applications in civil structure. One requirement from 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.

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 connections in the wireless unit. This dual-transceiver support affords the wireless sensing unit to be usable 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 900MHz band is for free public usage, such as the U.S., Canada, Mexico, and South Korea. Because the 900MHz band is not an unlicensed public band in Guangzhou, China, the 24XStream transceiver 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, an important procedure in signal conditioning is anti-aliasing that prevents high frequency signal and noise from irreversibly contaminating the data samples. The filtering circuits consist of a high-pass resistor-capacitor (RC) filter with a cutoff frequency of 0.014Hz and a low-pass 4^{th}-order Bessel filter with a selectable cutoff frequency of 25Hz or 500Hz. The phase shift of a Bessel filter varies linearly with frequency, which is equivalent to a constant time delay to the signals within the passband. This special property helps to maintain the waveform of the time-domain signal. In addition, the 4^{th} order provides sufficient steepness in the frequency response function for effectively eliminating high-frequency components. To serve different applications, a push-button switch is designed for conveniently alternating between the two cutoff frequencies (i.e. 25Hz or 500Hz). Using the signal conditioning module, the mean value of the analog sensor signal can be shifted to around 2.5 V, which is ready for digitization by the A/D module of the wireless sensing unit.

Although the 24XStream transceiver is claimed to have a communication range of 5 km at line-of-sight, the effective communication range may vary. For certain field condition, there are generally two ways to increase the wireless transmission distance, i.e. 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. 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 for the wireless sensing tests in the GTST. Our experiments demonstrated that using the 7.0 dBi antennas at both the transmitting and receiving side, a pair of 24XStream transceivers can reliably stream real-time acceleration data over a distance around 500m. Accordingly, to enable the long-range communication, the tradeoff is the relatively high power consumption of the 24XStream transceiver, which is rated as 150 mA during transmitting and 80 mA during receiving [27].

It should be noted that in addition to adopting long-range single-hop transmission (as used in this study) to achieve a long communication distance, an alternative approach is multi-hopping. The two approaches have their pros and cons. Using multi-hopping, the requirement to transmission range can be much lower, which may eliminate the need for high-gain antennas and long-range transceivers. In addition, under scenarios where heavy metal obstruction cannot be penetrated by the wireless signal, a relay unit will have to be adopted to circumvent such obstruction. On the other hand, reliable multi-hopping requires more complicated middleware implementation for the wireless units, due to the network complexity. By relaying data through multiple wireless nodes, longer communication latency is resulted, which makes real-time collection more challenging or unfeasible. Furthermore, all relaying nodes along the hopping path have to consume their 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.

3.3 Hardware calibration

In this study, both the wireless and the wired system adopt the same type of Tokyo Sokushin AS-2000C accelerometers, which have guaranteed output precision. However, considering one purpose of the study is to verify the precision of the prototype wireless system, a calibration of hardware devices is conducted.

Firstly, to calibrate the data acquisition precision and noise performance of the wireless unit, a laboratory calibration is carried out using standard sinusoidal signal as the input, in which a 0.1Hz single-frequency signal is generated by Agilent 33220A function generator. The sinusoidal signal is input into the signal conditioner for signal conditioning (x2000 amplification and anti-aliasing low-pass at 25Hz corner frequency) and output simultaneously into the wireless unit and one NI USB-6009 Data Ac-Quisition unit (DAQ), which has a 14-bit A/D conversion. 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 high purity of the acquisition results demonstrates that the wireless unit has a very good signal-to-noise ratio performance and does not add any unexpected noise to the measurement results.

Furthermore, apart from the laboratory calibration, an ambient environment calibration is conducted. In the experiment setup, ambient vibration signal generated by the GTST is collected by Tokyo Sokushin AS-2000C and input into the signal conditioner of the wireless system and then simultaneously output into the wireless unit and NI USB-6009 DAQ. Data acquisition results are as shown in Figure 7, in which the measurement results of both the wireless system and the NI USB-6009 DAQ are compared to that of the wired system. It is clearly observed that the PSD performance of data from the wireless unit has a close similarity with that of the NI USB-6009 DAQ and the wired system of GTST (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)).

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 testbed SHM system. In order to validate the performance of the wireless sensing system, six out of these twenty accelerometers are selected for providing baseline data in 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 X-direction and the other in 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)). The output signal of this additional accelerometer is then connected with a wireless sensing unit through the low-noise high-gain signal conditioning module (Figure 9). Simultaneously, the wired data acquisition system collects baseline data. The base station of the wireless sensing system, which receives the acceleration data from the wireless sensing unit, was located in the site office on 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 443m.

Table 1 Three heights at which wireless measurements are performed.

Height of the wireless accelerometers (m)	Wireless communication distance (m)	Storey
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 eliminate the effect caused by different signal conditioning 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 of the vibration data 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 unit and transmitted in real time to the server. Because the vertical axis of Figure 13 is set to the same scale as other figures to clearly illustrate 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 relatively noisy compared with the wired ones, they illustrate very similar waveforms. This shows that the wireless system was able to measure the ambient vibration 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. The table also illustrates that the resonant frequencies obtained from the wireless 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, PSD plot of the last 20 minutes (from the 40th to the 60th 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 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 443m. Although some wireless data is slightly more noisy compared with the wired data, the wireless measurements can provide accurate resonant frequencies of the tower. Most significantly, 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 supertall structures such as the GTST.

As the measurements of this work were conducted during the tower construction, many challenges due to the harsh environment have been confronted. Firstly, as shown in Figures 11-16, even though the wireless data is often as high-quality as the wired data, the wireless data can be influenced more often from environmental noise caused by construction activities. One reasonable explanation for this phenomenon is that the wired system has more reliable ground-connection for the power supply thus is better shielded (isolated) from external noise. Therefore, reduction of the environmental noises in the circuitry of the wireless system may be further improved in future designs.

Besides this preliminary application of wireless sensing technologies on monitoring the in-construction supertall structure, future study will be conducted to simultaneously collect acceleration measurements at different heights along the tower. Using simultaneous 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.

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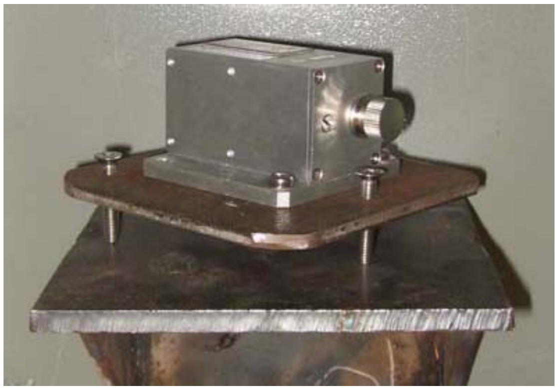
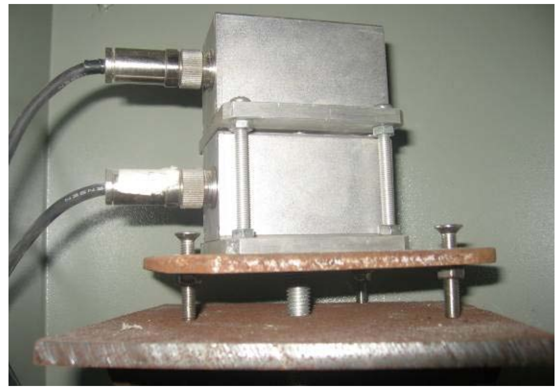
(a) July, 2007 (b) January, 2008 (c) January, 2009 (d) October, 2009

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

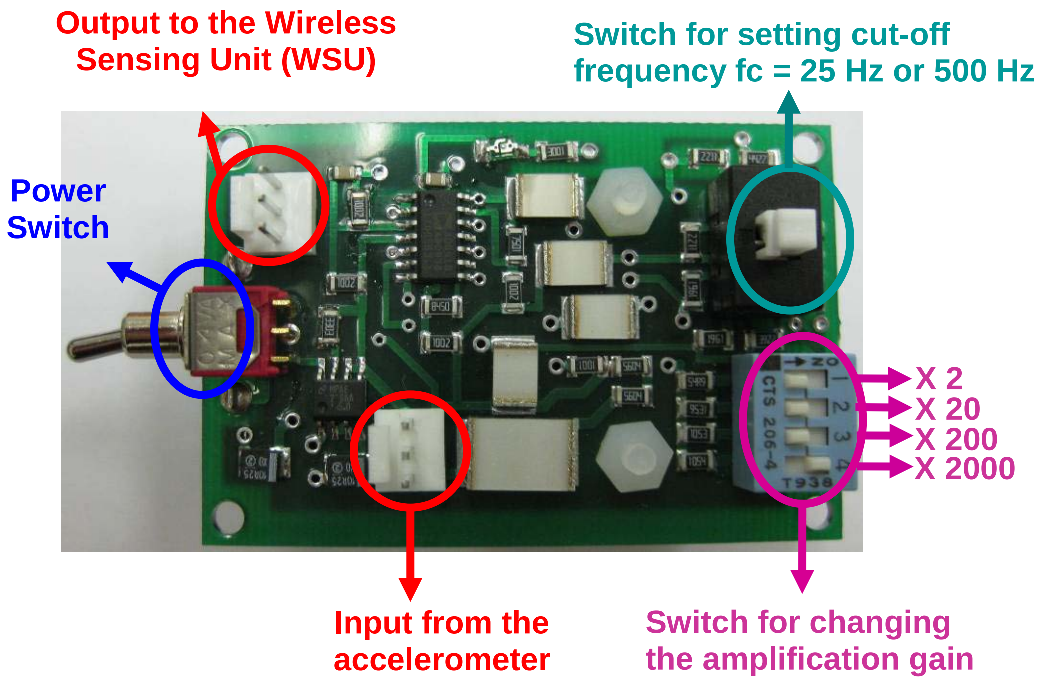


Figure 4. Low-noise high-gain (up to x2000) signal conditioning module

Figure 5. 7.0 dBi outdoor omni-directional antenna

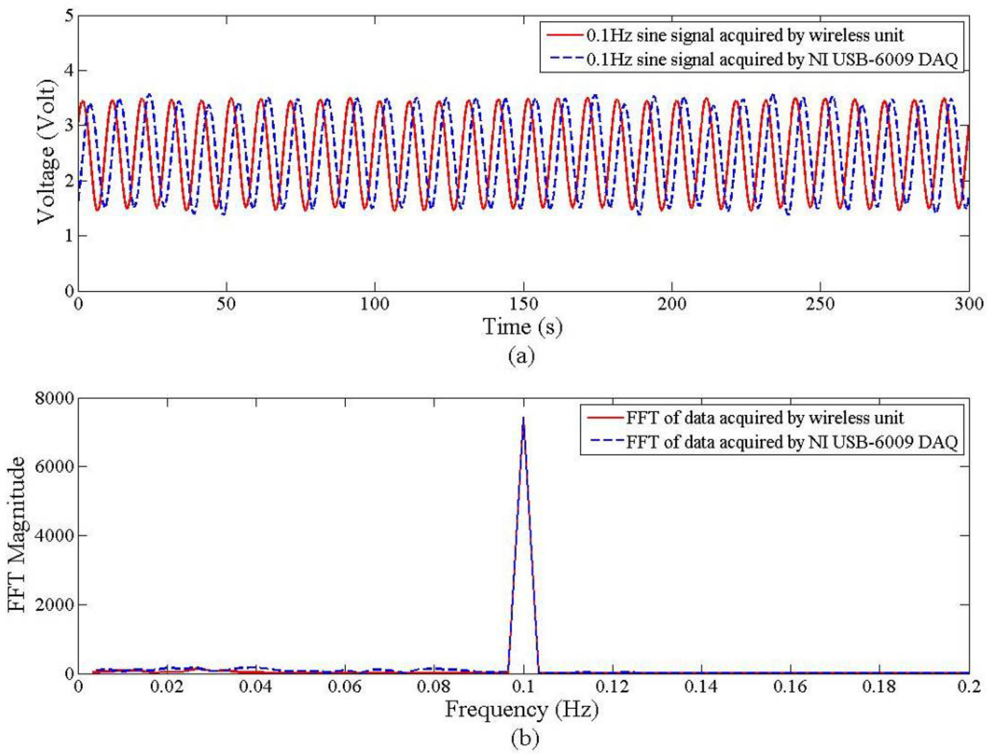


Figure 6. Wireless unit calibration using a standard sinusoidal signal generated by Agilent 33220A function generator: (a) Voltage data acquired by wireless unit and NI USB-6009 DAQ, (b) FFT magnitude

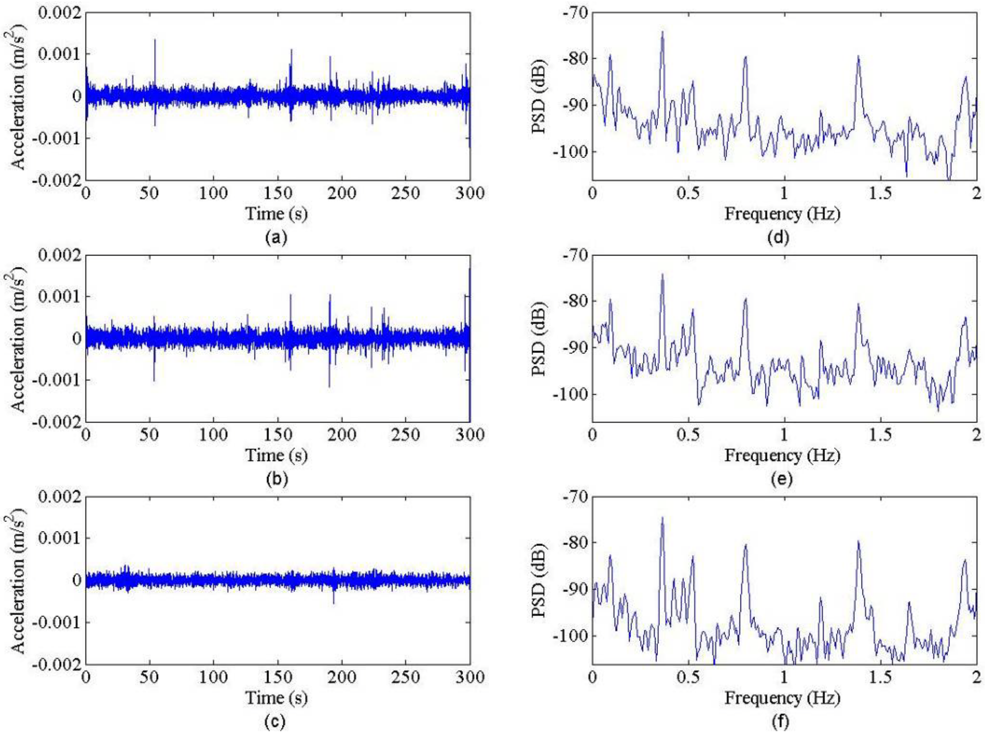
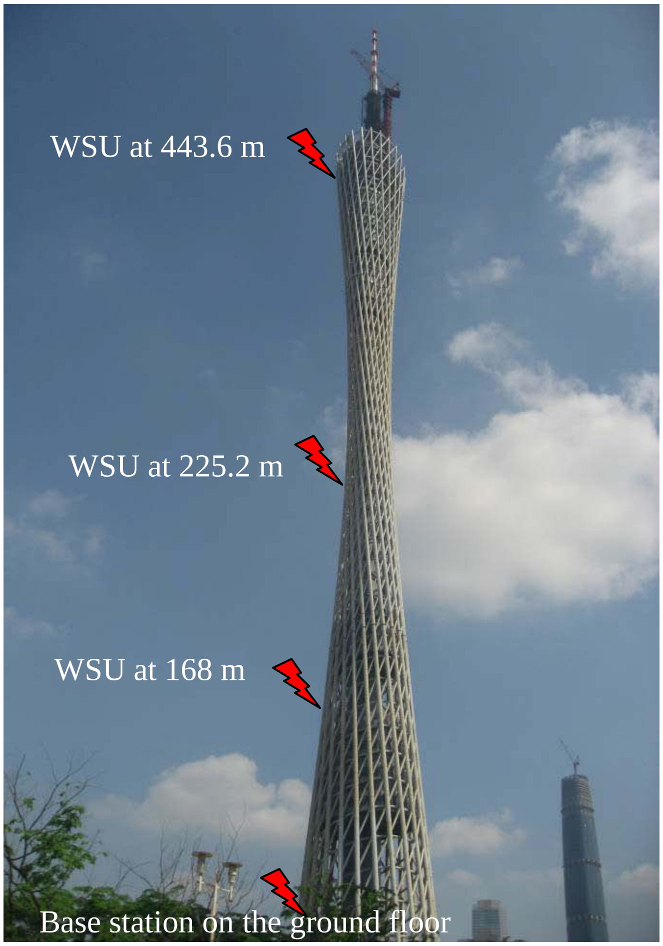
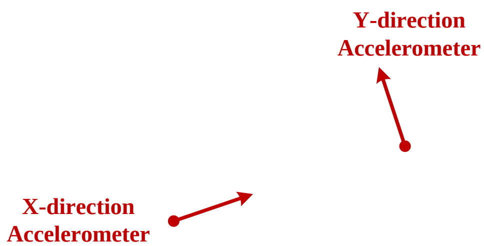


Figure 7. Wireless unit calibration using ambient vibration data of the GTST: (a) Acceleration acquired by wireless system, (b) Acceleration acquired by NI USB-6009 DAQ, (c) Acceleration acquired by wired system, (d) PSD of data acquired by wireless system, (e) PSD of data acquired by NI USB-6009 DAQ,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

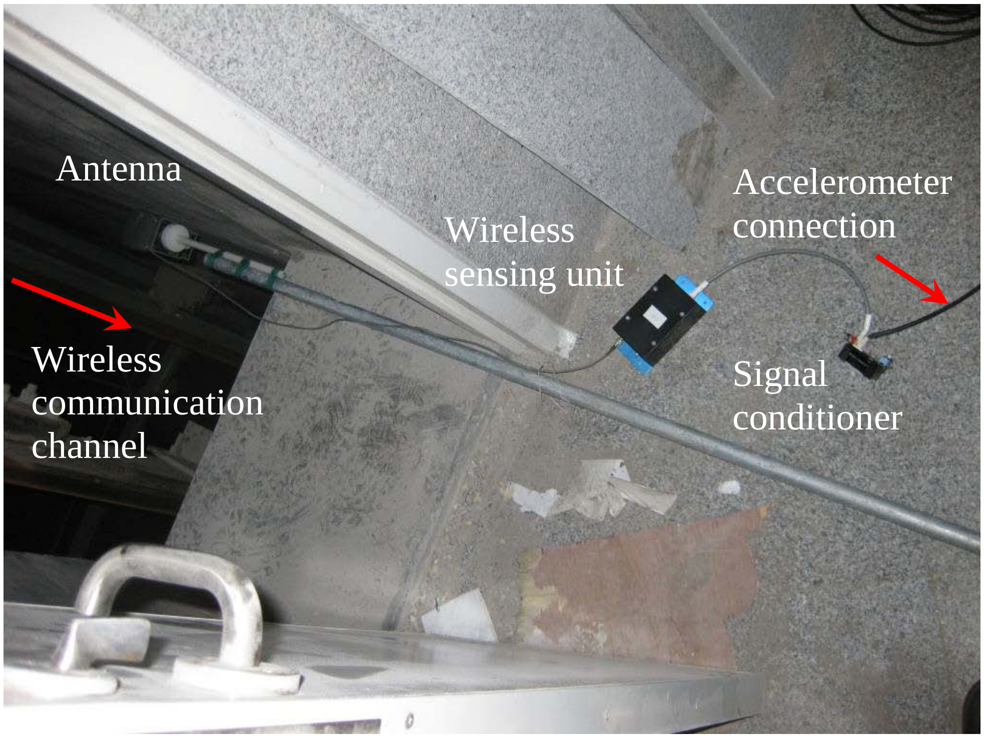


Figure 9. Experimental setup of the wireless sensing unit and the associated signal conditioning module inside the GTST

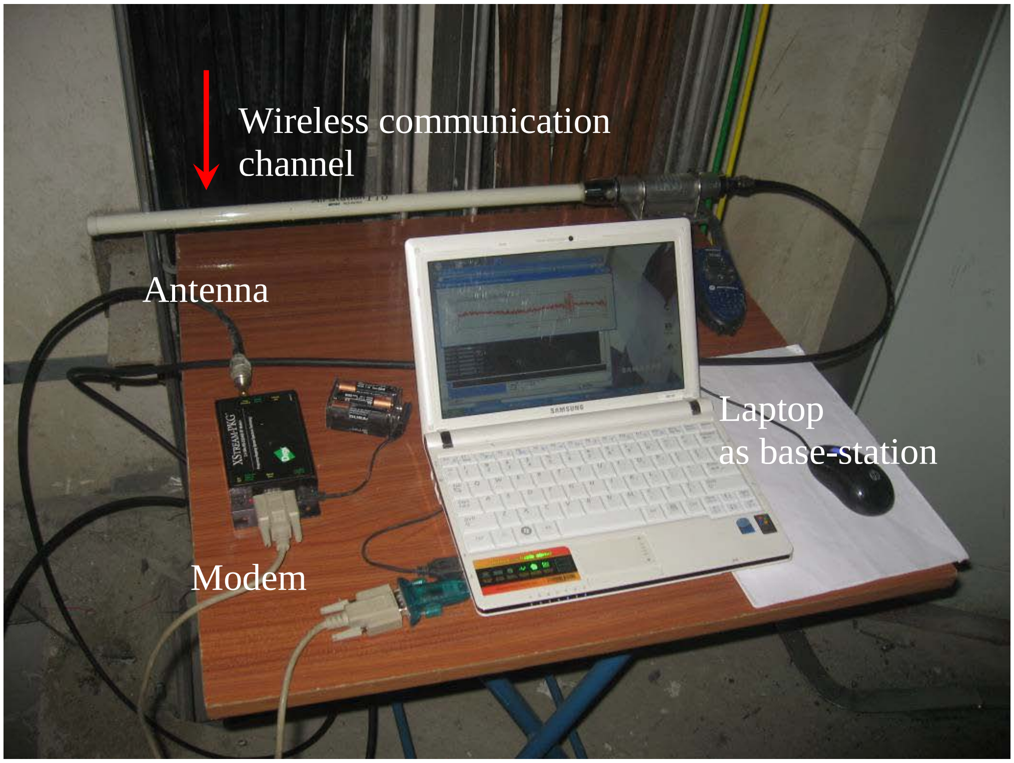


Figure 10. Experimental setup of the wireless base station at the site office on ground level

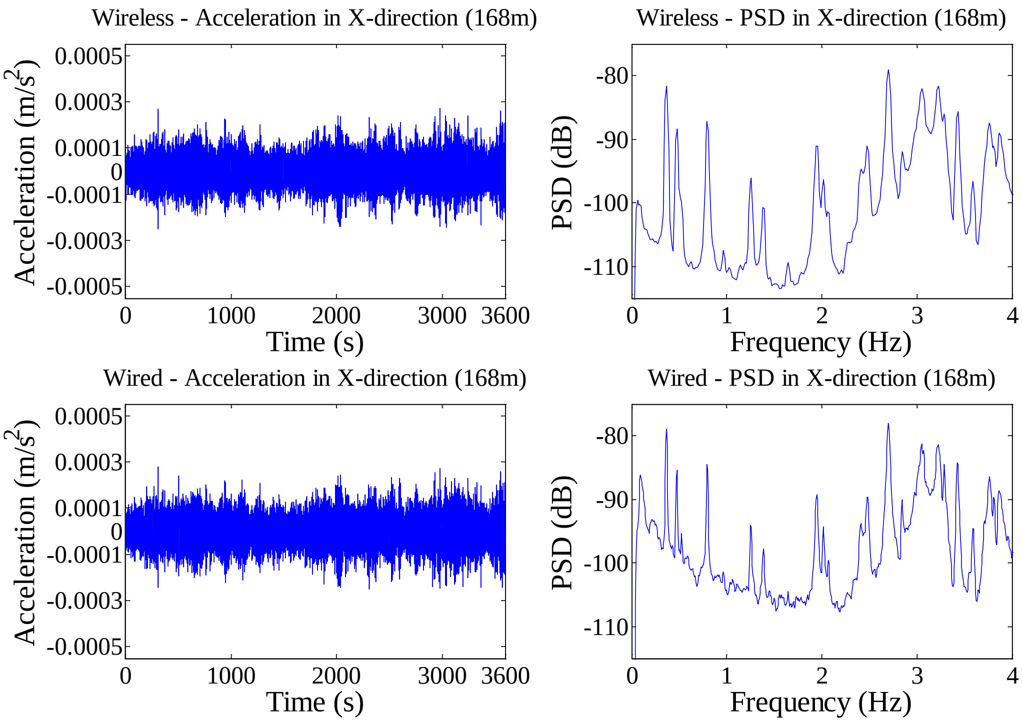


Figure 11. Ambient vibration signal of the GTST (Left: time history; Right: frequency domain) from an X-direction accelerometer at 168-m height received by the wireless sensing system (top) and the wired data acquisition system (bottom)

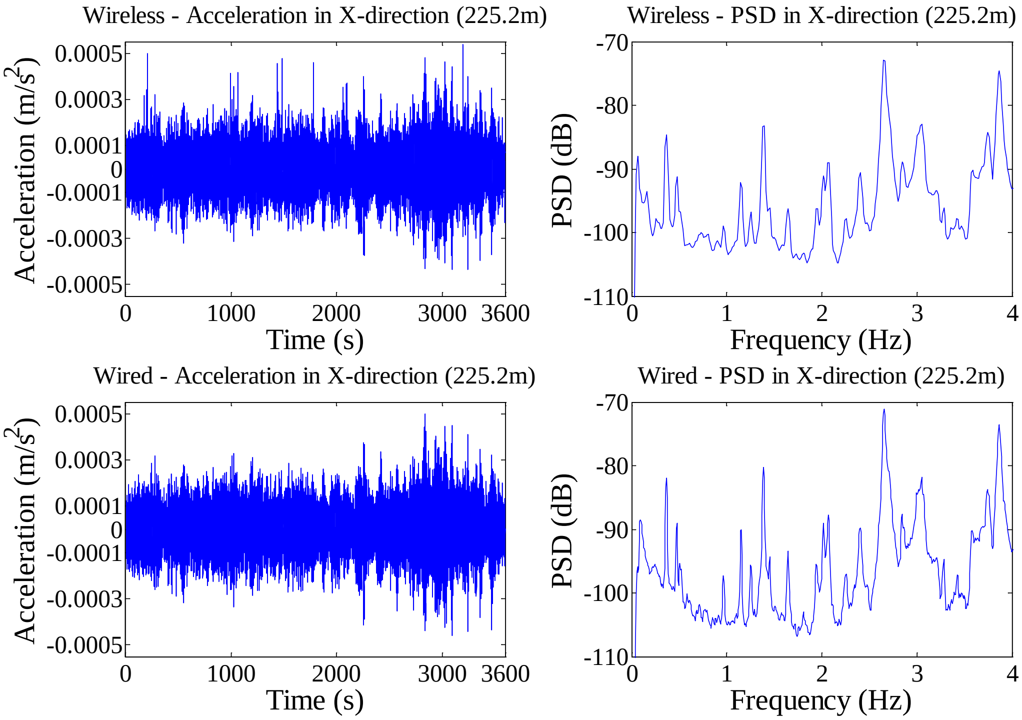


Figure 12. Ambient vibration signal of the GTST (Left: time history; Right: frequency domain) from an X-direction accelerometer at 225.2-m height received by the wireless sensing system (top) and the wired data acquisition system (bottom)

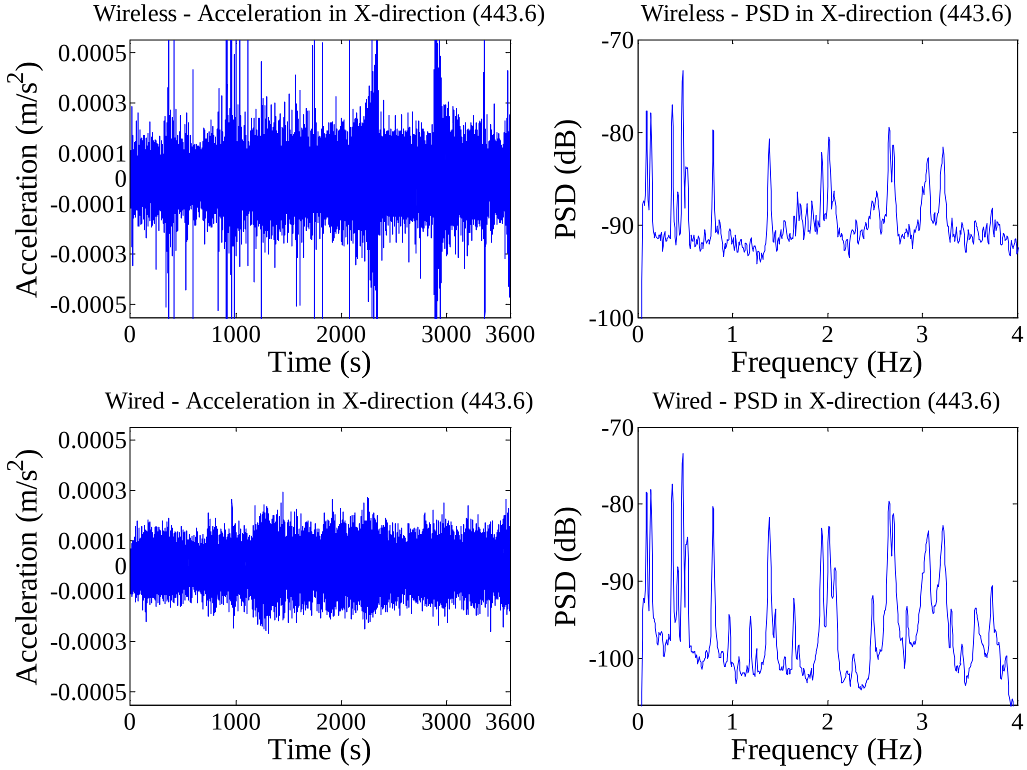


Figure 13. Ambient vibration signal of the GTST (Left: time history; Right: frequency domain) from an X-direction accelerometer at 443.6-m height received by the wireless sensing system (top) and the wired data acquisition system (bottom)

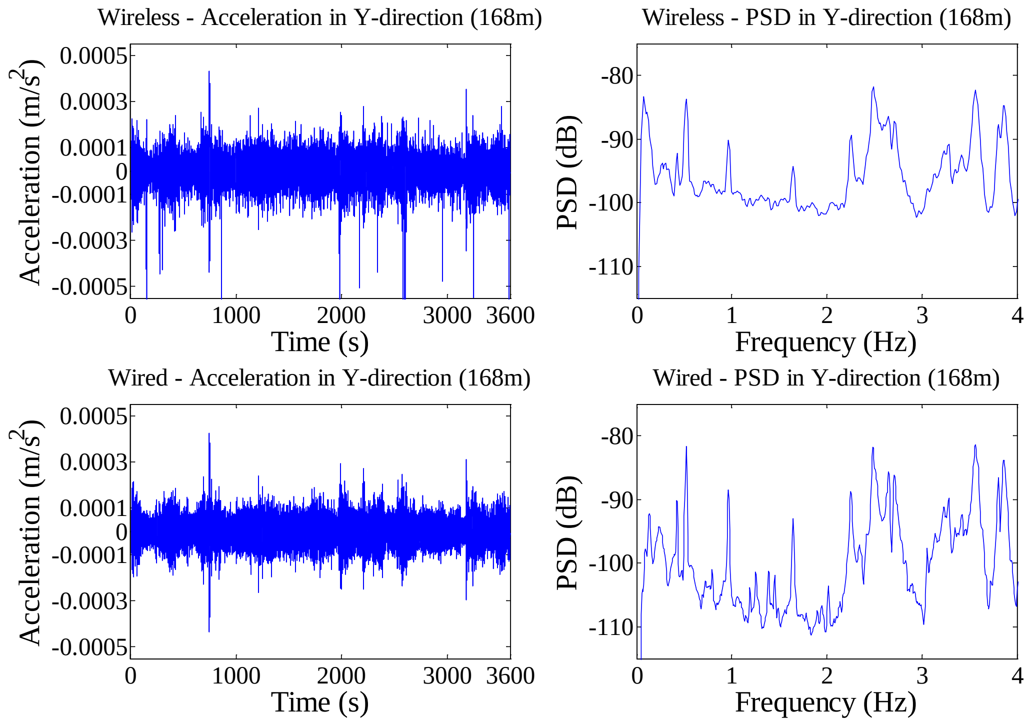


Figure 14. Ambient vibration signal of the GTST (Left: time history; Right: frequency domain) from a Y-direction accelerometer at 168-m height received by the wireless sensing system (top) and the wired data acquisition system (bottom)

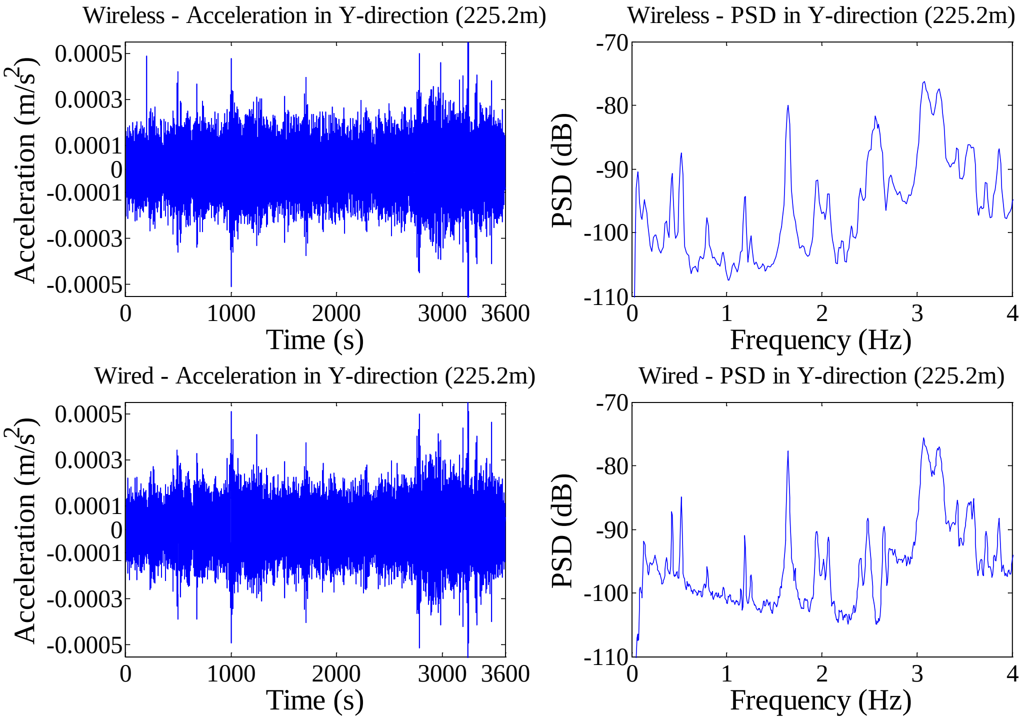


Figure 15. Ambient vibration signal of the GTST (Left: time history; Right: frequency domain) from a Y-direction accelerometer at 225.2-m height received by the wireless sensing system (top) and the wired data acquisition system (bottom)

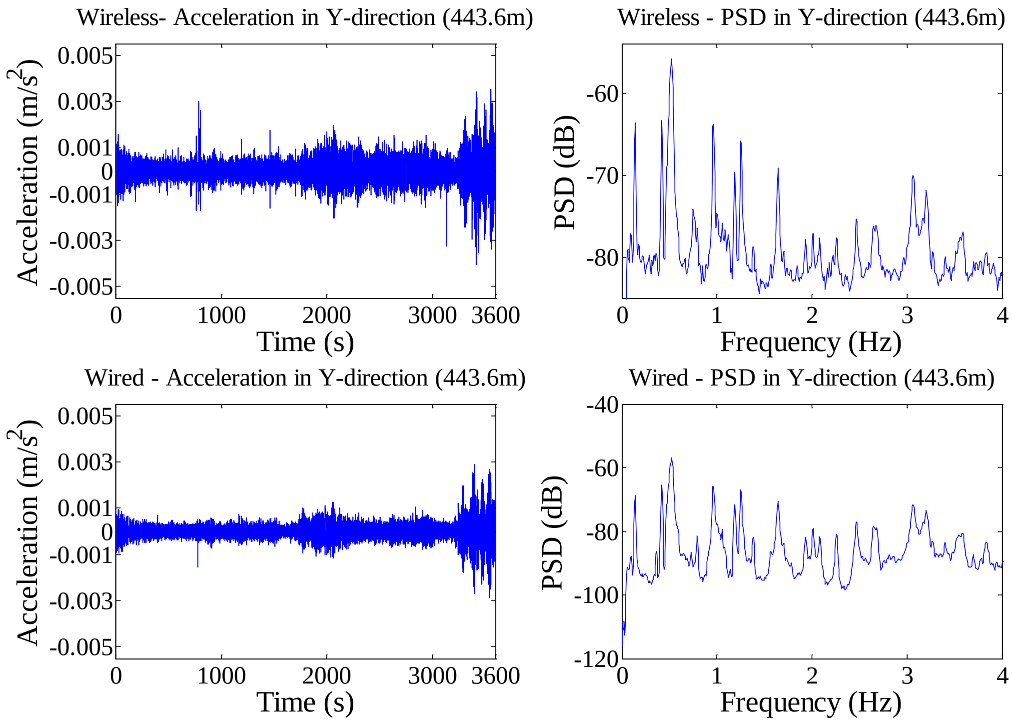


Figure 16. Ambient vibration signal of the GTST (Left: time history; Right: frequency domain) from a Y-direction accelerometer at 443.6-m height received by the wireless sensing system (top) and the wired data acquisition system (bottom)

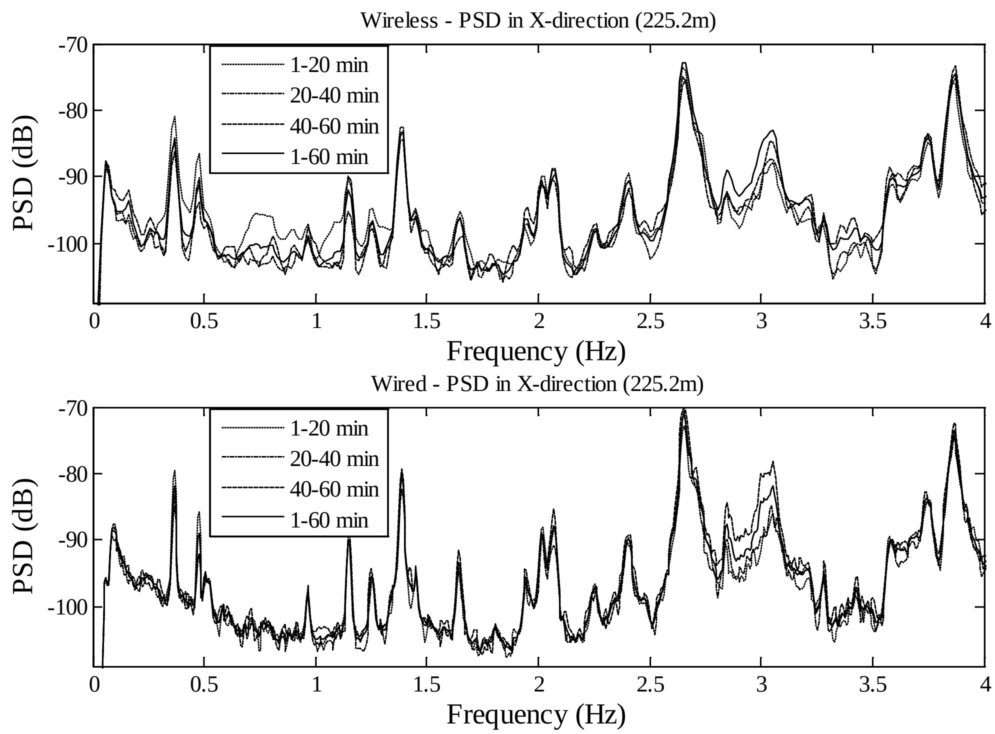


Figure 17. PSD performance of data within different segments of an hour (the data was collected by an X-direction accelerometer at 225.2-m height and simultaneously acquired by the wireless sensing system and the wired data acquisition system)

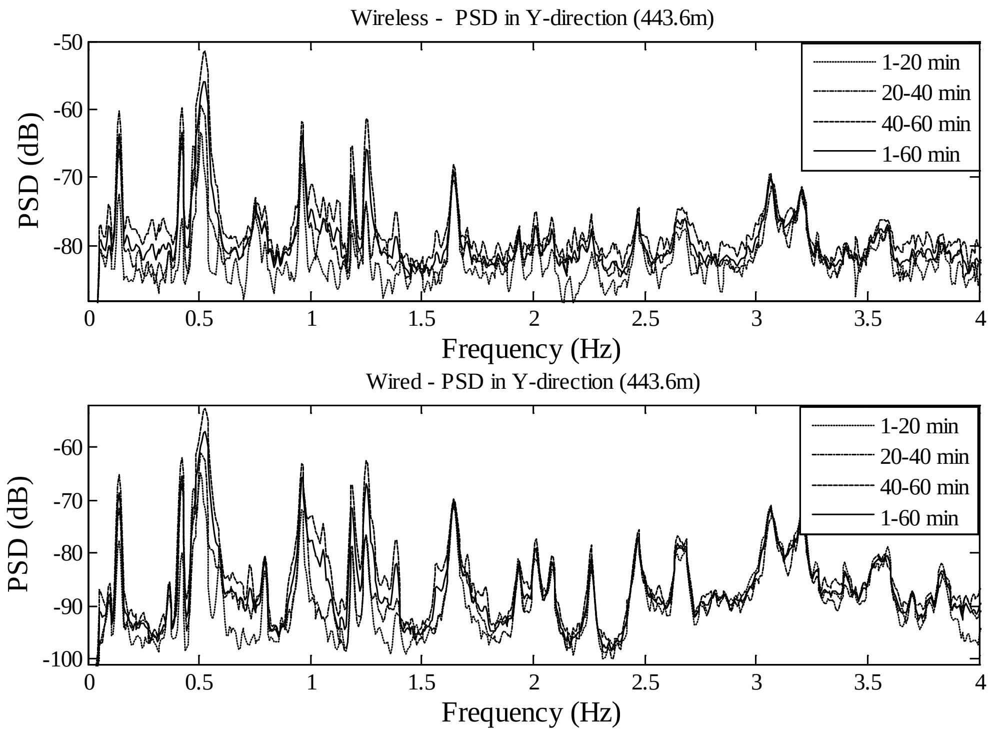


Figure 18. PSD performance of data within different segments of an hour (the data was collected by a Y-direction accelerometer at 443.6-m height and simultaneously acquired by the wireless sensing system and the wired data acquisition system)