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A remote long-term and high-frequency wind measurement system: design, comparison and field testing

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Abstract. The wind field measurement of severe winds such as hurricanes (or typhoons), thunderstorm downbursts and other gales is important issue in wind engineering community, both for the construction and health monitoring of the wind-sensitive structures. Although several wireless data transmission systems have been available for the wind field measurement, most of them are not specially designed for the wind data measurement in structural wind engineering. Therefore, the field collection is still dominant in the field of structural wind engineering at present, especially for the measurement of the long-term and high-frequency wind speed data. In this study, for remote wind field measurement, a novel wireless long-term and high-frequency wind data acquisition system with the functions such as remote control and data compression is developed. The system structure and the collector are firstly presented. Subsequently, main functions of the collector are introduced. Also novel functions of the system and the comparison with existing systems are presented. Furthermore, the performance of this system is evaluated. In addition to as the wireless transmission for wind data and hardware integration for the collector, the developed system possesses a few novel features, such as the modification of wind data collection parameters by the remote control, the remarkable data compression before the data wireless transmission and monitoring the data collection by the cell phone application. It can be expected that this system would have wide applications in wind, meteorological and other communities.

Keywords: wind field measurement; remote control; data compression; wireless data transmission; cell phone application; integration

1. Introduction

Accurately acquiring wind characteristics is an important issue in the wind and meteorological engineering communities (Huang *et al*. 2015, He *et al*. 2017, Peng *et al*. 2018). Due to its directness and accuracy, the field measurement is widely to obtain the first-hand wind speed data (Solari *et al*. 2012, Zhang *et al*. 2018, Burlando *et al*. 2018). Currently, many instrumentation systems have been used for different purposes. To measure short-term hurricanes and thunderstorm downbursts, the mobile instrumented tower can be swiftly employed (Schroeder and Smith 2003). To obtain the long-term wind data, temporarily established masts or towers (Cao *et al*. 2009) and permanent structural health monitoring systems (Wang *et al*. 2013) can be adopted.

With the economy development in mountainous areas, especially in China, more long-span bridges, transmission towers and other structures have been built (e.g., Xiang and Ge 2007). To better design these wind-sensitive structures, the wind characteristics should be well studied. The field measurement provides most accurate approach for the wind field and gains more attention. The wind profiler, Doppler radar, Windcube Lidar and other advanced instruments are used for the wind field measurement in mountainous area (Heo *et al.* 2003; Cohn *et al.* 2011, Yu *et al*. 2019, Liao *et al*. 2020). When the fluctuating component of the wind speed is focused, high-frequency anemometers, such as ultrasonic anemometers are preferred (Turnipseed *et al.* 2003). During measurements, the wind data were typically collected by an onsite computer or a data collector (such as CR1000 data logger by Campbell Scientific) or radio transmitter/receiver (Turnipseed *et al.* 2003, Subramanian *et al.* 2005). These instruments require collecting data manually, or provide non-real-time data via the internet, or need a separate base station to receive the measured data and the transmission distance is limited (no more than 10km), thus they are not suitable for the wind field measurement in the remote mountainous area.

Along with the rapid development of the communication technology, GPRS or UMTS/HSPA/HSUPA wireless network is adopted in engineering practice (Zhong *et al*. 2014, Zheng *et al*. 2018). For example, CR3000 data logger by Campbell Scientific and NI Compact RIO by National Instrument are two typical integrated collectors which adopt wireless networks to transmit data and have applications in

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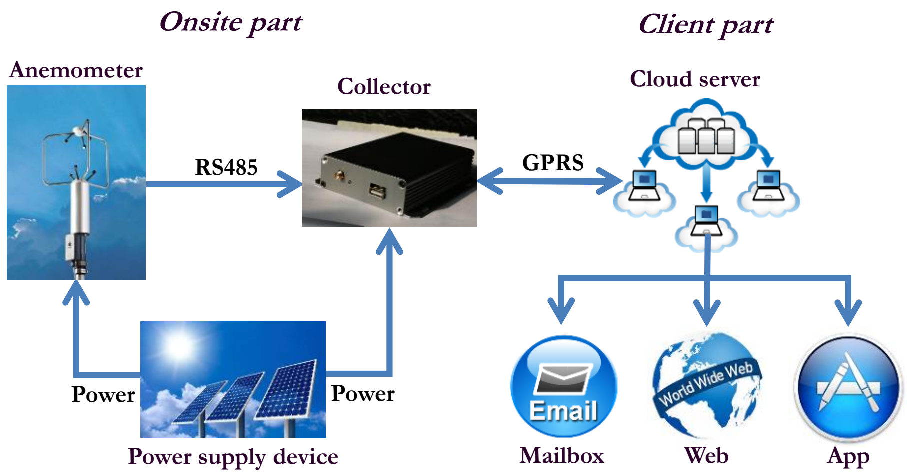


Fig. 1 System architecture

multiple areas. Song *et al*. (2013) developed a structural health monitoring system based on the wireless sensor network. Otero *et al*. (2009) and Subramanian *et al*. (2005) introduced wireless instrumentation system in wind speed and pressure measurement during hurricane events. To acquire remotely the long-term and high-frequency wind data in the remote mountainous area, the authors developed a wireless transmission instrumentation system by assembling commercial remote terminal unit modules (Huang *et al*. 2015, Huang *et al*. 2019). Overall, these systems have following disadvantages. Firstly, users cannot remotely modify data parameters such as the sampling frequency and wind speed threshold. Hence, the alternation of these parameters in the remote area is rather difficult. Second, all measured data by the anemometer are transmitted wirelessly, and the transmission efficiency is relatively low. This could be a problem for the remote mountain areas, where the transmission signal is relatively weak.

The application of remote laboratory technology for enhancing engineering education has attracted much attention in the last decades (Wang *et al*. 2017). With the real time experiment control and data transmission solution, the end user can control remote experiments and view experimental data on the web browser (Wang *et al*. 2015). However, to the best of the authors' knowledge, the remote control and real time data transmission have been not applied for the long-term and high-frequency wind data acquisition.

In order to be more convenient and efficient for the wind field measurement in remote areas, based on the previous developed system by the authors (Huang *et al*. 2015), this study develops a wireless high-frequency data acquisition system with the remote control, data compression and other functions. The innovations and scientific contributions of this paper are listed as follows. (1) The proposed system can acquire the real-time, long-term and high-frequency wind data. (2) The wind data can be acquired in the user-defined format by the remote control function. (3) The collected data and the working status of the system can be monitored in real time through the mobile phone. (4) A field test shows that the proposed system has well-pleasing performance in terms of the data loss rates and system stability.

This paper is organized as follows: firstly, the system architecture and the data collector are presented; then, novel functions of the system and the comparison with existing systems are addressed; furthermore, the performance of the proposed system is evaluated; finally, the conclusions will be given.

2. System architecture

To achieve the remote wind field measurement, the wireless wind data acquisition system is composed of the onsite part and the client part, as shown in Fig. 1. The anemometer, data collector and power supply device constitute the onsite part. An ultrasonic anemometer, Young 81000, which is widely used to measure high-frequency wind data, is selected as the example in the demonstration. The data from the anemometer is wired to the collector via RS485 cable. The collector has data storage, processing and transmission, and other functions. The detailed description and associated functions will be explained in Section 3. The power supply device adopts double batteries. In the operation, the larger one is functional and the smaller one is backup. The double batteries can improve the stability of power supply. Two meters are used to display the power and voltage of batteries. The solar power or wind and photovoltaic hybrid power will be used to offer the energy to the anemometer and collector.

The client part includes the cloud server, and related mailbox, web and cell phone application (App). As shown in Fig. 1, these two parts of the system are connected through the wireless communication between the collector and cloud server. This connection is via GPRS wireless network, which is based on the specified Transmission Control Protocol/Internet Protocol (TCP/IP). Due to the existence of the mutual communication between the collector and cloud server, not only the collected data can

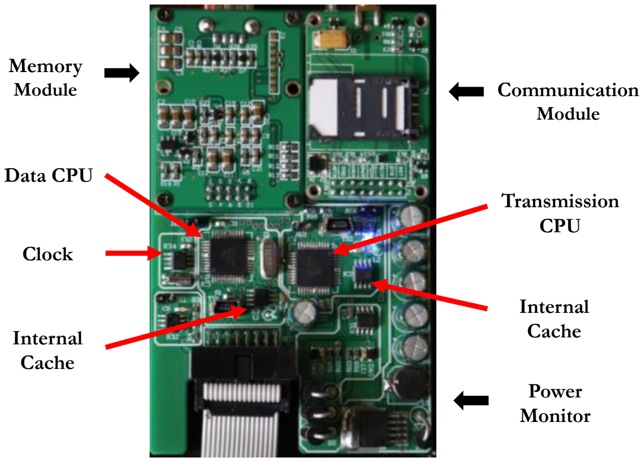


Fig. 2 Composition of collector

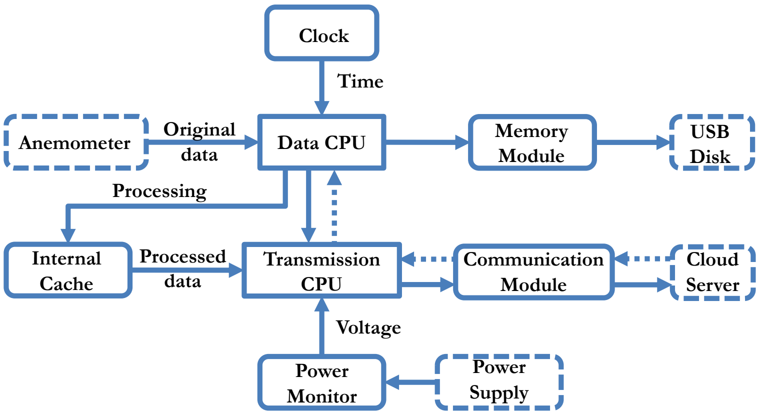


Fig. 3 Flow chart of wind data treatment

be transmitted to the cloud server, but also the demands from the user such as the change of wind data parameters can be sent to the collector as well. The detailed discussions will be addressed in section 3. Web and cell phone App are developed to monitor the system operation and release the warnings, which will be also discussed in Section 4.3. The mailbox is used to receive wind data for the user.

3. Data collector

As the core component of the acquisition system, the collector is a specific application of Single Chip Microcomputer (SCM) based on the integrated circuit technology, as shown in Fig. 2. It mainly consists of 7 working elements: 1-the clock, 2-data CPU, 3-memory module, 4-internal cache, 5-transmission CPU, 6-communication module and 7-power monitor. How the data are handled by these elements is addressed here.

Usually, the output data of the anemometer are not tagged with the time. During the data transmission, the data may be lost or repeated due to the network interruption, power shortage and other technical problems. Clearly, it will be very hard to restore the order of these data without the time tag. Hence, the clock is used to tag the time to the wind data. In this manner, DS1302 produced by DALLAS company in America is used, which is a low power clock chip with trickle current charging capability. In fact, the clock is an electronic timer, consisting of a lithium battery and a clock chip. In order to avoid the accumulated error on the timer, the cloud server will use the network time to adjust the clock at regular intervals, such as 1 month.

The data CPU is firstly used to tag the time from the clock to the raw data from the anemometer. In addition, the data CPU commands the memory module to save the data with time tag (in original sampling frequency of the anemometer) to the external storage such as USB disk. These data serve as the backup. This is because the data in the wireless transmission may be lost. Note that when the sampling frequency is 20 Hz, which is the maximum sampling frequency of the anemometer, a 16G USB disk can store about one-year data. Furthermore, the data CPU will manipulate the data according to the user's request (such as downsampling wind data and setting wind speed threshold) and compress the manipulated data to improve the transmission efficiency. The detailed treatment will be presented in section 4. Finally, the compressed data will be stored to the internal cache and the data CPU will send the message that the data can be transmitted by the transmission CPU when the storage of the internal cache is full. Note that the CPU in this system adopts the industrial grade AT89S52-24AU produced by the American ATMEL

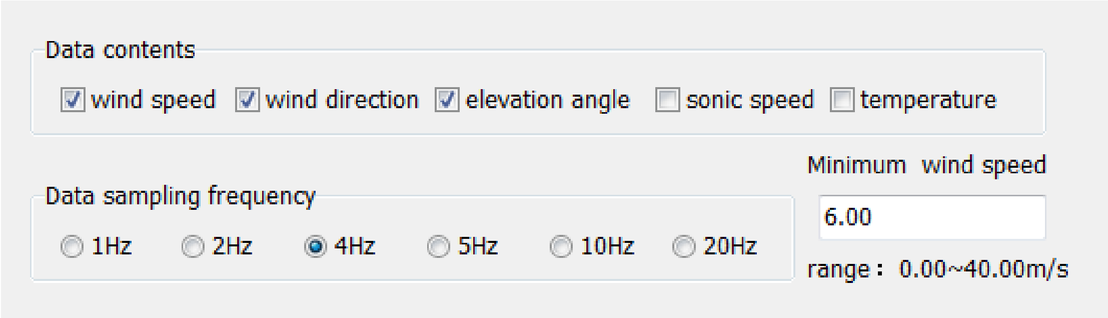


Fig. 4 Close-up of remote controlling interface

company. The chip is compatible with the MCS-51 instruction system, and has three 16-bit programmable timing/counter with clock frequency of 0~33 MHz. It has the advantages of low power consumption, idle and power-saving mode, dual data register pointer and so on, and is widely used in the field of watchdog (WDT) circuits, etc.

The internal cache is used for the temporary storage of the data that wait for the transmission, i.e., the compressed data are not transmitted immediately to cloud server, but sent out once a certain amount of the data are accumulated. This treatment is due to the energy conservation and possible transmission instability. Since a single cache chip cannot write and read data simultaneously, a series of chips are required. In this system, eight 1M cache chips are selected as the internal cache of the collector. The processed data are firstly saved to 8 chips in order, and then the data in each full chip are sent out promptly in the first-in first-out (FIFO) order. If data are collected by 20 Hz, the internal cache can approximately store 1-hour data, which means that the system can tolerate 1-hour wireless network interruption. That should be enough to cope with the problems such as the network maintenance and unstable signal in remote mountainous areas. For this system, the cache chip adopts the industry-level AT24C1024 produced by the American ATMEL company. The chip provides 1,048,567 bits of serial erasable and programmable read-only memory (EEPROM), each 8 bits of which constitute a byte, a total of 131,072 bytes. The device's cascading capabilities allow up to two devices to share the same 2-wire bus.

The transmission CPU sends the data stored in the internal cache and the voltage from the power monitor to the cloud server through the communication module after it receives the message from the data CPU. What’s more, the communication module can receive requests (changing wind data parameters) from the user via the cloud server and send them to the data CPU. Accordingly, data CPU can work following the changed wind data parameters. Note that the communication module uses SIM900A as the core component. This module is a compact GSM/GPRS module, using SMT package and ARM926EJ-S architecture with strong performance. It transmits wind data and receive user’s requests through the external SIM card using GPRS network.

The power monitor is used to supervise whether the system is out of power by collecting the real-time voltage of the power supply device. This is because in remote areas, the power supply of the anemometer and collector relies on solar or wind energy, which heavily depends on the climate, and the stable supply may not be guaranteed.

The flow chart describing the wind data treatment is shown in Fig. 3.

4. Novel functions of acquisition system

In addition to aforementioned features such as the wireless transmission for wind data and hardware integration for the collector, many other functions beneficial to the system application in practice will be discussed hereafter.

4.1 Remote control

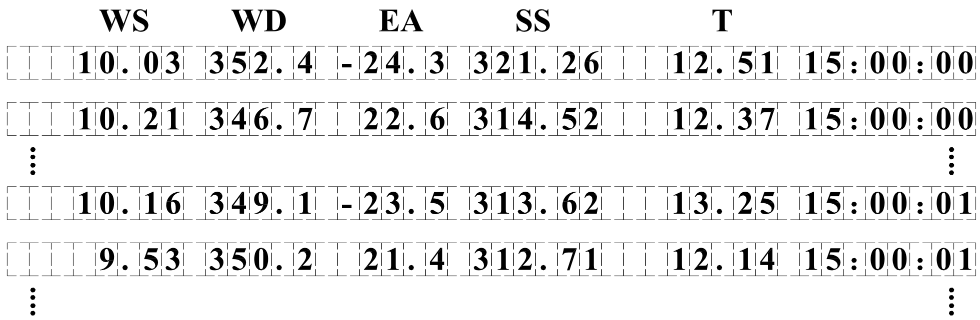
As mentioned in section 3, the request from the user can be sent to the collector via the cloud server. Then the collector can follow the user’s instruction to collect the data. In this system, the parameter of wind data to be transmitted can be changed according to user’s request. Young 81000 will be used as the example to demonstrate how to control the collector remotely via changing wind data parameters.

As shown in Fig. 4, three options can be used to alternate the parameters of wind data: data content, sampling frequency and minimum wind speed. Clearly, the output data from the anemometer contain five items: wind speed, wind direction, elevation angle, sonic speed and temperature. Any item can be selected in the measurement.

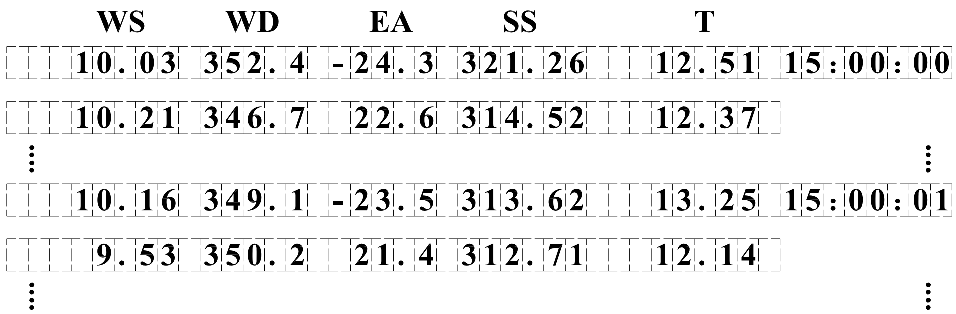
Before the system installation on site, the sampling frequency of the anemometer (or original sampling frequency) should be specified. In this application, it is 20 Hz. As mentioned previously, original sampling frequency can be downsampled. In this system, 6 frequencies could be chosen: 20, 10, 5, 4, 2 and 1 Hz.

Usually, the very small wind takes a large portion, but it is not useful. According to the previous study on the wind in the mountain areas, about 80% of the wind speed is less than 6 m/s (Huang *et al*. 2016; Huang *et al.* 2019). Hence, a minimum wind speed can be specified as the threshold, under which the wind data will be discarded.

For the wind field measurement of a large-span bridge in the remote mountain valley, first three items should be selected, while the last two can be neglected. The sampling frequency can be selected as 4 Hz and the minimum wind

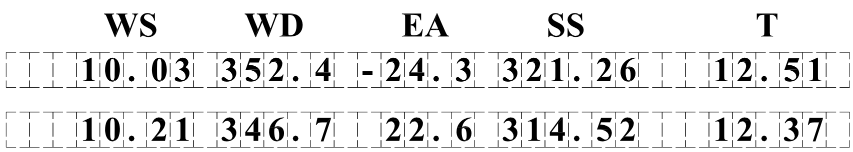


(a) Before reduction

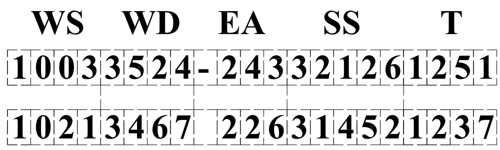


(b) After reduction

Fig. 5 Reduction of time tag redundancy



(a) Before elimination



(b) After elimination

Fig. 6 Elimination of unimportant characters

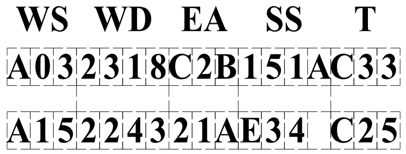


Fig. 7 Hexadecimal conversion

speed could be 6 m/s. These selections can be found in Fig. 4. For other applications, different parameters can be adopted by the user. By the remote control, the user can conveniently filter out the unwanted data, which can significantly improve the efficiency of data transmission and reduce the workload in the wind data analysis.

4.2 Data Compression

The transmission of the long-term and high-frequency wind data will impose the large challenge to the wireless network, especially for the remote mountainous area where the network may be not stable and the signal is weak. Data compression can reduce the workload on the network and improve the efficiency of the transmission. In the proposed system, the compression focuses on the reduction of the time tag redundancy, the elimination of the unimportant characters and hexadecimal conversion of wind data.

If the raw data of every sampling are tagged with the time information including hour, minute and second, the redundancy will be unavoidable, as shown in Fig. 5(a), where WS, WD, EA, SS and T denote wind speed, wind direction, elevation angle, sonic speed and temperature,

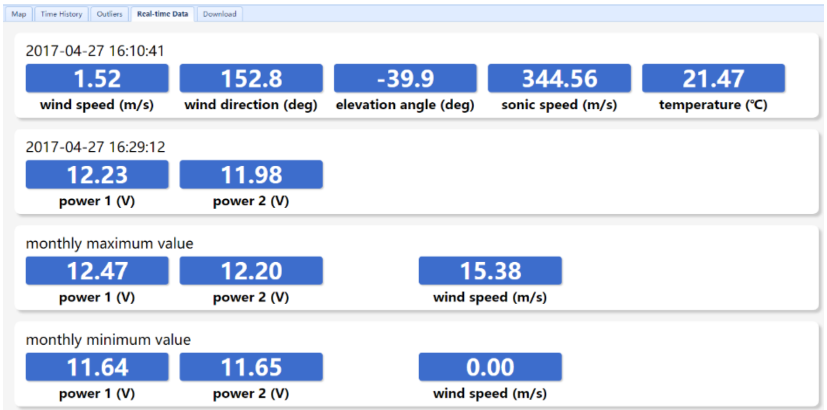
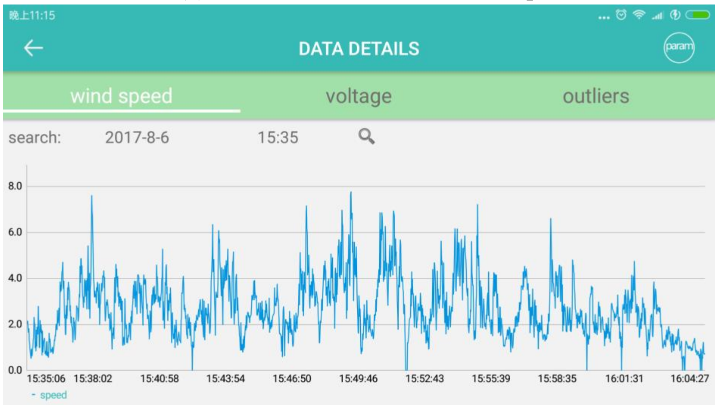
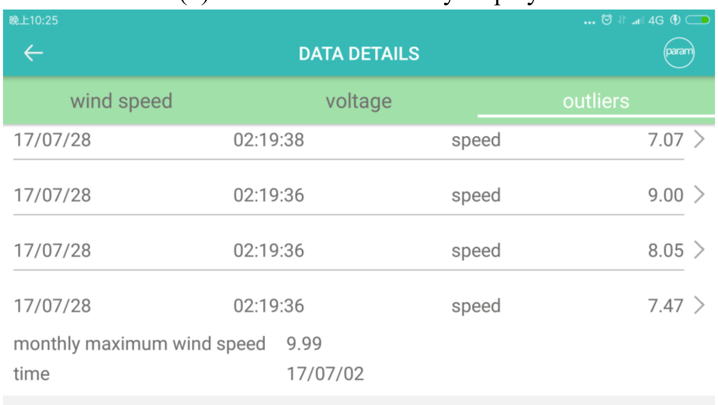


Fig. 8 Web-based real-time data

(a) Anemometer locations on map



(b) Real-time time history display



(c) Outliers

Fig. 9 App interface

Table 1 Comparison of different wireless data acquisition systems

Features	System 1	System 2	System 3	System 4
Integration	yes	yes	no	yes
Remote control	no	yes	no	yes
Data compression	no	no	no	yes
Cell phone app	no	no	no	yes

respectively. Actually, the time information is not necessary to be assigned to the data of every sampling. In this proposed system, only the data corresponding to the first sampling in every second are tagged with the time, as shown in Fig. 5(b). Further reduction is possible according to the user.

In the output data of the anemometer, it can be found that several spaces and decimal points take the fixed positions for the sampled data, as shown in Fig. 6(a). These unimportant characters can be eliminated during the data transmission only if their positions are remembered. In this way, the transmitted data can be reduced, as shown in Fig. 6(b).

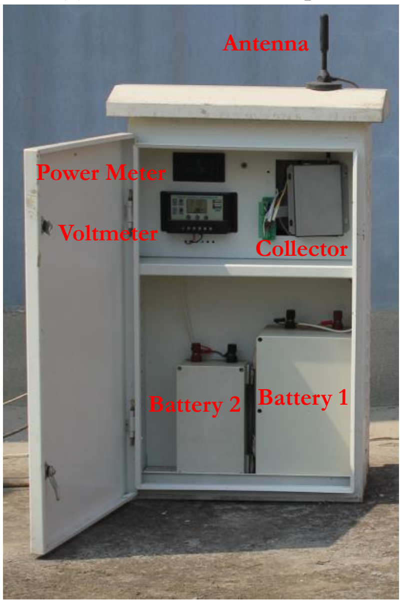
In this system, the decimal number will be converted to the hexadecimal number. Since the wind speed, wind direction and temperature have 4 effective digits, every 2 neighboring digits can be converted to 1 or 2-digit hexadecimal number. The elevation angle has 3 effective digits and 1-digit sign, which could be negative ("-") or positive (empty space). Here "-" and empty space can be replaced by "1" and "0", respectively. Hence, the elevation angle will have four digits and converted to hexadecimal numbers following the aforementioned conversion. The sonic speed has five effective digits. Because the sonic speed is in the range of 300-400 m/s, the first digit should be 3. Accordingly, the following 4 digits can be converted to hexadecimal numbers. The detailed conversion for data in Fig. 6(b) is shown in Fig. 7.

With the elimination of unimportant characters and the hexadecimal conversion of wind data, the data can be compressed by about 50%. Considering the reduction of time tag redundancy, the data will be compressed further. Overall, the demand on the data transmission will be greatly reduced. In addition, some other data compression methods are used by other researchers, such as differential coding (Timmermann 2001), RLE (Capo-Chichi *et al*. 2009), Huffman coding (Wang and Zhang 2017), LZW coding (Malik *et al*. 2017), arithmetic coding (Saarinen 2017), etc. They can reconstruct the compressed data without distortion and restore the original data accurately. Some of these methods can be also used in the proposed system, which will be investigated in our future works.

4.3 Web and cell phone application

The data files can be packed automatically, and sent to a prescribed email address regularly (every 1 hour) or saved in the database by the cloud sever. In addition, to better display and monitor the wind speed data, the web and cell phone application are also developed based on the saved data. The real-time data are monitored conveniently on the web, which is shown in Fig. 8. For simplicity, the real-time histories of wind speed and voltage, the anemometer location and warning function for large wind speed and unusual voltage are not addressed here.

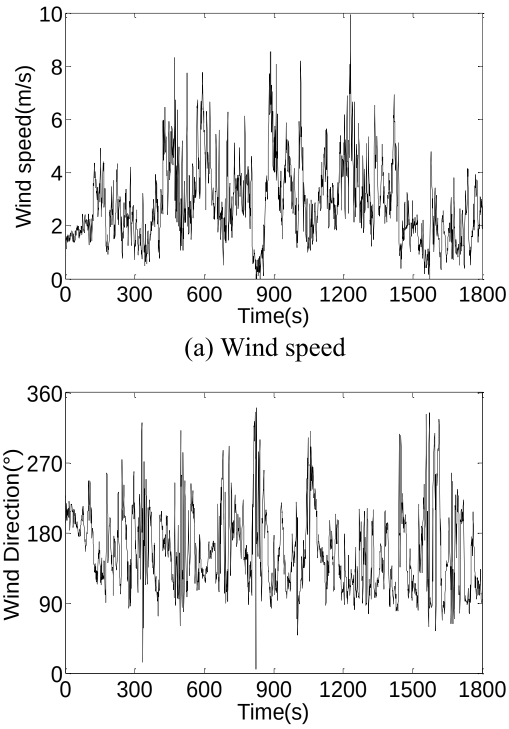
(a) Overview of onsite part



(b) Power supply and collector

Fig. 10 Application of proposed system

To monitor the measured data more conveniently, cell phone app is developed. In this app, any anemometer can be located on the map, as shown in Fig. 9(a). The time history of wind speed for any half hour and the trend of the voltage can also be examined, as shown in Fig. 9(b). Furthermore, the outliers can be released as the warnings to the user if the wind speed or voltage is beyond the predefined limit. Fig. 9(c) shows the record of the outliers. Through the outlier table, user can find the happening time for the outliers and obtain the corresponding time history.



(b) Wind direction

Fig. 11 Selected wind speed sample

Table 2 Data loss rates

Date	Loss rate (%)	Weather	Date	Loss rate (%)	Weather
4 Jun 2017	0.38	Rain	3 Aug 2017	0.38	Cloudy
5 Jun 2017	0.37	Rain	6 Aug 2017	0.38	Rain
24 Jul 2017	0.37	Rain	26 Sep 2017	0.38	Cloudy
25 Jul 2017	0.37	Rain	27 Sep 2017	0.37	Cloudy
26 Jul 2017	0.39	Cloudy	1 Oct 2017	0.97	Cloudy
2 Aug 2017	0.37	Cloudy	2 Oct 2017	0.51	Rain

5. Comparison with other existing systems

In order to clearly display the advantages of the proposed system, it is compared with other similar devices. Within the scope of the author's knowledge, there are few wireless transmission devices specially used for the long-term and high-frequency wind speed data collection at present, and the field collection is still dominant in the field of structural wind engineering (He *et al*. 2017, Wang *et al*. 2018). For the sake of generality, the aforementioned CR3000 and NI Compact RIO for the wind field measurement are used for the comparison. In addition, the previous developed system by the corresponding author (Huang *et al*. 2015) specially used for wind speed data collection is also compared. They are referred to as System 1, 2 and 3, respectively. The proposed system is referred to as System 4.

Table 1 compares these four wireless acquisition systems in terms of integration, remote control, data compression and cell phone app, and it shows that the performance of the system 4 has been significantly improved, especially manipulating wind data parameters by the remote control and significantly higher data transmission efficiency. Admittedly, CR3000 and NI Compact RIO have more excellent functions that can be used in other different fields. In this section, only the specific application of wireless wind speed data acquisition in structural engineering is compared.

6. Performance evaluation of proposed system

To evaluate the performance of the proposed system, the onsite part of the wind data acquisition system was installed on the roof of XNJD-3 wind tunnel in Southwest Jiaotong University, as shown in Fig. 10. After about 6-month wind field measurement, Table 2 summarizes data loss rates in typical days. It is found that the system is very stable with very little data loss. The wind speed and wind direction for the duration of 1800 s are shown in Fig. 11.

7. Conclusions

In this study, a remote high-frequency wind data acquisition system was developed. This newly-developed remote system has multiple novel functions. Firstly, wind data acquisition parameters can be alternated by the remote control, which provides the significant convenience to the user. Secondly, the data can be compressed remarkably before the wireless transmission. This feature is very useful to the remote area, where the wireless transmission rate may be low. Thirdly, the cell phone application gives the user the convenient approach to monitor the data collection. Clearly, this proposed system can be extended to collect other types of data such as the acceleration and wind pressure. It is expected that this system would have wide applications in wind, meteorological and other communities.

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