# Structural Health Monitoring of the Support Structure of Wind Turbine Using Wireless Sensing System

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# STRUCTURAL HEALTH MONITORING OF THE SUPPORT STRUCTURE OF WIND TURBINE USING WIRELESS SENSING SYSTEM

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**ABSTRACT**

The wind turbine heavily depends on the success of the support structure to resist the complicated environmental loading, especially for the offshore wind turbine. How to manage these wind turbines and monitor the structural safety becomes an urgent and important issue today. To monitor the support structural safety of wind turbine, a good understanding of the structural dynamic behaviors of wind turbine is preliminary requirement. Due to the complicate dynamic behaviors of realistic wind turbine which includes the effects of the soil-structure interaction (SSI), the machine operation loading, the wind interaction, etc..., both the numerical model study and the system identification are required to clarify these complicated structural behaviors.
In this study, a wireless sensing system, NTU-WSU, is installed in an on-shore large wind turbine (GE 1.5MW) to collect the structural responses, and the system performance of the proposed NTU-WSU was also evaluated in this study. Three measurement layouts and two operational scenarios (operating and stop states of the wind turbine) are considered in this study to clarify the complicated structural dynamic behaviors. Two system identification approaches are adopted in this study to extract and verify the structural dynamic features, direct Fourier spectrum observation method and frequency domain decomposition (FDD) method.

**KEYWORDS :** *wind energy, structural health monitoring, wireless sensing, frequency domain decomposition.*

## INTRODUCTION

With the getting serious problem on energy shortage, the demand for renewable energy is increasing, and the wind energy is gaining popularity as one of the most practical alternative today. Currently, through the development of wind energy, the number of wind turbine is substantially increasing. In order to minimizing the environmental impact and increasing the power generating efficiency of wind turbine, the development of offshore wind farm is in full swing. The wind turbine heavily depends on the success of the support structure to resist the complicated environmental loading, especially for the offshore wind turbine. How to manage these wind turbines and monitor the structural safety becomes an urgent and important issue today. An integral SHM-System for offshore wind turbine was proposed by *Rolfes et al.* [1] and the concept of the monitoring on the structural safety of the support structure was also introduced. A review of damage detection methods for wind turbine system[2] *Ciang et al.*, provides the damage probability of each components of wind turbine and reviews several structural damage detection methods, especially on the damage of blade.
In order to monitoring the structural safety of wind turbine, the scientists and engineers must make a good understanding on the structural dynamic behaviors of wind turbine. The realistic dynamic behaviors of wind turbine are very complicate with the effects of soil-structure interaction (SSI),

 

machine operation loading, wind interaction, etc. To clarify these complicated structural behaviors, both the numerical model study and the system identification on realistic structural responses are necessary. An experimental and numerical investigation into seismic response of wind turbine were presented by *Prowell, I. et. al.*[3], a full scale shaking table test of wind turbine was performed and both numerical study and system identification from the experiment were presented.

Traditionally, to deploy a wired sensing system on a large scale structure (bridge, dam, wind turbine, etc.) is expensive and environmental restraint. To shortening the instrumentation time, reducing cost and breaking through the environmental restraint, the wireless sensing technology is widely adopted in recent decades. A study on the structural monitoring of wind turbines using wireless sensor networks was presented by *R. Andrew Swartz, et. al.*[4], a wireless sensing system was adopted to two wind turbines and a roughly dynamic features were extracted in this experiment.

In this study, a wireless sensing system, NTU-WSU which is purposed for civil structural vibration measurement, is installed in an on-shore large wind turbine (GE 1.5MW) to collect the analysis required structural responses signals and demonstrate the system performance in this unique operational environment. In this paper a wireless sensing system, NTU-WSU, was adopted to collect the structural responses of an on-shore wind turbine in Taiwan. The overview of NTU-WSU is presented. The dynamic features of wind turbine, modal frequencies and mode shapes, are illustrated with two analysis techniques, fourier spectrum observation and frequency domain decomposition [5].

## 1 WIRELESS MONITORING OF WIND TURBINE

To validate the proposed wireless sensing system (NTU-WSU) for their applicability of wind turbines, this study implements the NTU-WSU system on measuring the structural vibration responses of a large on-shore wind turbine. Moreover, the behaviors of support structure of wind turbines could be realized by utilizing well-developed system identification techniques to extract the structural dynamic features. In this study, the one of the on-shore wind turbine (GE 1.5MW) in Taiwan are temporarily considered as the test bench for evaluating the applicability of the wireless sensing system on the structural monitoring of the support structure of wind turbines. The support structure of this on-shore wind turbine is a 68 meters height tower with gravity type foundation. The wireless sensing system, monitoring scenarios, sensor instrumentation, and signal analysis results would be introduced in the following sections.

### 1.1 Wireless sensing system (NTU-WSU)

In this study, the wireless sensing system (NTU-WSU), developed by NCREE and NTU, and the high sensitivity velocity meter (VSE-15D1), designed by Tokyo Sokushim Co., Ltd., are adopted as the structural monitoring system of wind turbine to prevent the difficulties on sensor wiring and layout in the support structure of wind turbine.

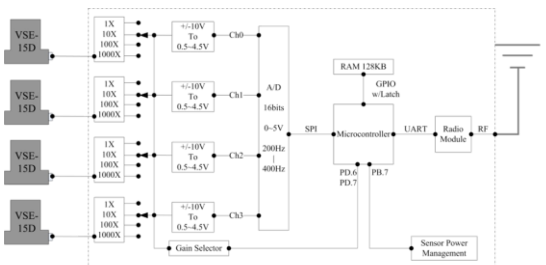

Figure 1: NTU-WSU architecture and photo

NTU-WSU inherited the main architecture design of Wireless Modular Monitoring System (WiMMS) that is an 8-bits RISC microcontroller based embedded system with 128kB external SRAM, 4 channels 16bits Analog-to-Digital Converter and wireless module. The 8-bits RISC

microcontroller, ATmega128, controls the peripheral devices of wireless sensing unit and handles the computation of data pre-processing; The external SRAM, CY62128, buffers the sampled row data and the variables that generated by the analysis program, the maximum buffered data length is 64k points (unsigned short); the 16-bits Analog-to-Digital Converter, ADS8341EB, converts the analog voltage signal to discrete digital row data; two different purposed wireless modules, 9XTend and 24XStream, are compatible with NTU-WSU and creates the data linkage of wireless sensor network of measurement system. The basic architecture of NTU-WSU is shown in **Figure 1**.
Based on this architecture, the requirement on the monitoring of structural ambient responses is additionally considered in NTU-WSU. On sensor signal sampling, NTU-WSU provides two signal adjustment stages, the first stage is amplifying signal with optimal pre-amplifying gain and the second stage is scaling and shifting signal into the sampling range of ADC. There are four sensor input channels in a wireless sensing unit and all of them with a programmable gain amplifier (PGA204) to pre-amplifying sensor signal and is controlled by microcontroller (ATmega128). Another improvement on the signal sampling of NTU-WSU is the oversampling process, this process achieves the ADC sampling with a rarely high speed (limited by the performance of ADS8341EB and is about 100kHz) and downs sample to the configured sampling rate (Fs). The oversampling process performs three advantages on signal sampling, and they are avoiding aliasing, improving resolution and reducing noise [15]. NTU-WSU provides 5 different sampling rates, Fs, (50, 100, 200, 500, 10k Hz) and when the oversampling function is achieved, the oversampling time is 128 for 50Hz, 64 for 100Hz, 32 for 200Hz, 16 for 500Hz and 1 for 10kHz. The oversampling process is shown in **Figure2**.

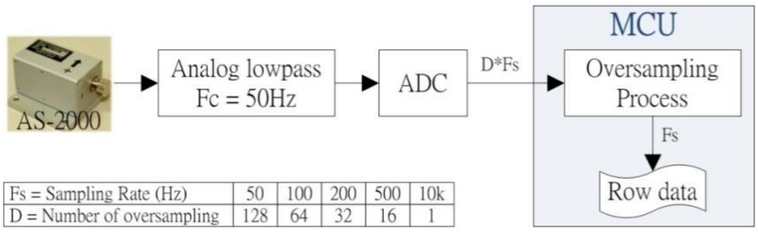

Figure 2: The oversampling process of Sensor Node.

The NTU-WSU is compatible with two different wireless modules, Digi 9XTend and 24XStream. The 9XTend is operated in 900 MHz; 24XSream is operated in 2.4 GHz. By the selection of wireless module, the NTU-WSU can prevent the busy frequency band of RF in the test environment. The data rate and communication range of 9XTend module is better than 24XStream; the power consumption of 9XTend is also larger than 24XStream. NTU-WSU can adopt with a suitable wireless module to match the application requirements of different structural monitoring scenarios.

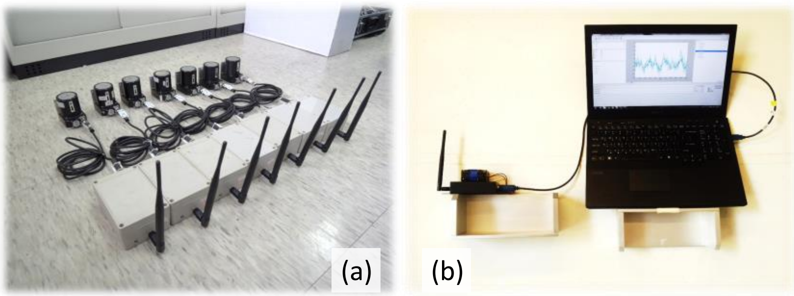

Figure3: (a) The calibration of wireless sensors. (b) The server and wireless receiver of wireless sensors

The entire wireless sensing system still needs a laptop as the server. The server provides the functions of data storage, signal analyzing and sensor management. The entire wireless sensing system must make sure that the sensitivities of all sensors in this system are calibrated, to perform this calibration, all sensors are co-located and recorded at the same time segment and the sensitivities are evaluated through the comparsion of the signals of different sensors. Figure 3(a) shows the calibration procedures for wireless sensing system. Figure 3(b) shows the server of wireless sensing system which includes the laptop and wireless receiver.

## 1.2 Wind turbine instrumentations

In this study, the measurement target is the support structure of a GE 1.5MW on-shore wind turbine which is constructed of circular hollow sections and is totally 68 meters in high. Due to the geometric symmetry of the support structure and the eccentric loading of tower induced torsional responses, the structural behaviors are complicated and is difficult to be presented in two dimensional space (XZ, YZ plane), and the three dimensional structural responses are required to perform the analysis of system identification. Each measurement point is installed with one set of three dimensional velocity meter, which is consisted of three uniaxial velocity meters (VSE-15D1). To investigate the soil structure interactions between the tower foundation and soil, the responses of free-field and tower foundation are required to collect the features of soil structure effect. The measurement point U3, Unit No.3 of wireless sensing system, is used to measure the free-field ground motions and was located on the center of the grass which is 100 meters away from the tower. Moreover, to perform the structural behaviors of the gravity type foundation of wind turbine in this study, U4 and U5 are installed on the symmetry points of the circular foundation plate. Duplicated measurement points in a cross-section is necessarry to make a good understanding on the vibration motion of the cross-section and to realize the minimum requirement on the sensor layout in a cross secion. The velocity meter (VSE-15D1) is expensive (about US$5000) and the number of VSE-15D1 is limited in the wireless sensing system, to get the complete structural responses base on this constrain, the most effective measuring arrangement in this study includes three types of sensor layout (Case1 ~ Case3), **Figure 4** is the schematic layout of Case1~3 and the details are as follows:

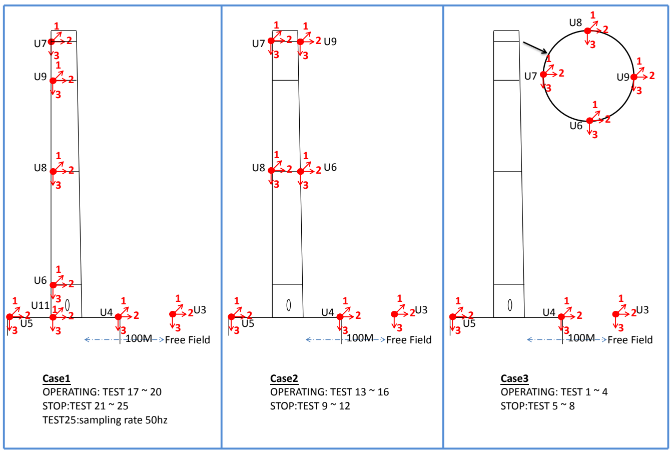


Figure 4: The arrangement of sensors on the wind turbine tower

- Case1: The vibration signals measurement from the elevation view. Five different elevations are picked to locate the sensors on the tower as equal spaced as possible. By observing the measured responses of these elevation sensors, the three primary mode shapes of the support structure could be illustrated in elevation view.
- Case2: The complex motions of the wind turbine must be well addressed. Therefore, the torsion effects are considered as well as two horizontal directions and one vertical direction. As a result, the cross sections of top and middle elevations of the tower are picked as the observing targets. The sensors are arranged on each cross section symmetrically. The whole 3D motion of the tower is well illustrated by the six sensors.
- Case3: Due to the assembly mass of the wind power generator is almost the same as the tower, the wind turbine model can be roughly simplified to a single circular hollow column with a eccentric point mass on the top and six degrees of freedom (x,y,z,ϴx, ϴy, ϴz) are considered in the point mass. To illustrate all motions of the point mass, there are four measurement points on the top of the tower.

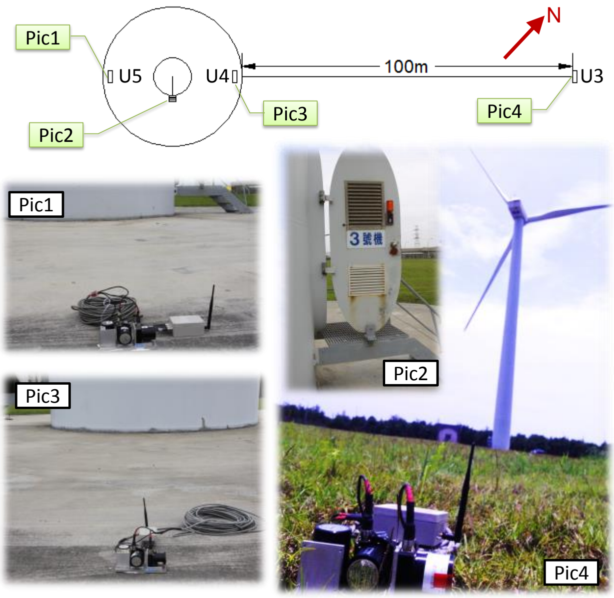


Figure 5: Photos of measuring equipment: outside the tower, near foundation, and in the free-field.

Both the parked and operating conditions of the wind turbine are considered in this study. For the parked condition, the structural responses are mainly induced by the light disturbances in the environment which is not so complicated. Therefore, these structural ambient responses could be utilized to conceptualize the dynamic features of the support structure of the wind turbine. However, on the condition of operating, the responses of the wind turbine contain a great number of other disturbances, such as the machinery vibration of power generator, aerodynamics, and the soil-structure interaction under large deformation in the foundation. Therefore, the responses under the operating condition contain great numbers of information which could be used to analyze many interactions between the foundation and other forcing effects. To perform enough data for the following-up analysis, there are 4 tests in each instrumentation case, and each test measured 1 minute response histories with 200Hz sampling rate.

The measurement equipment is shown in **Figure 5** and **Figure 6**. Two symmetrical positions for measuring are on the gravity type foundation. The 3-direction velocity meter is adhered to the foundation by gypsum. For the free field sensor, the velocity meter is installed on the top a short pile, which is embedded into the soil. An laptop serves as the server of the wireless sensing system and is installed at the bottom of the inner-side of the circular hollow tower. The door of the manhole is open to make sure the communication performance of the wireless sensing system. The instrumentation of Case3 for measuring on the top of the tower are shown in **Figure 6(a)**. **Figure 6(b)** shows the velocity meter in the tower is fixed on an aluminum box which is magentic adsorption for the inner surface of the tower.

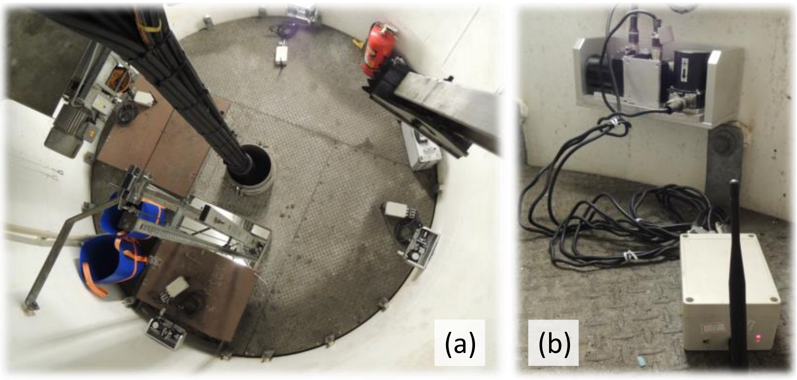


Figure 6: Photos of measuring equipments inside the tower and the fixation of micro-vibro-meter.

## 2 RESULTS AND DISCUSSION

The measuring of the responses of the wind turbine tower costs totally 1.5 days. We made three instrumentations of the sensors along the tower (Case1 ~ Case3), and obtained 25 sets of the vibration responses (TEST1~25). The complete observing information is shown in **Table 1**.

Table1: Information for measuring of the wind turbine (2013/6/13 ~ 14)

| Sensor layout | Condition | Test number | Date | Note |
|---|---|---|---|---|
| Case 1 | Parked | TEST 21~24 | 6/14 (11:47 ~ 12:05) | |
| | Operating | TEST 17~20 | 6/14 (11:27 ~ 11:47) | |
| Case 2 | Parked | TEST 9 ~ 12 | 6/13 (16:38 ~ 16:50 | |
| | Operating | TEST 13 ~ 16 | 6/13 ( 17:02~ 17:12) | |
| Case 3 | Parked | TEST 5 ~ 8 | 6/13 (14:30 ~ 14:44) | |
| | Operating | TEST 1 ~ 4 | 6/13 (14:09 ~ 14:20) | |
| The sampling rate is 200 Hz.<br>The measured response is velocity with unit Kine (cm/sec).<br>TEST25 is with the same measuring setup of TEST24 but the sampling rate is 50Hz, and its history duration is 4 minutes. | | | | |

In this study, only the signals measured from the sensors arranged along the tower (Case1) were presented. The following section illustrates the analysis results in the parked condition (TEST24) and operating condition (TEST20).

**Figure 7** shows the structural response signals in the parked and operating conditions. The velocity response on the top of the tower is 100 times larger than the one on the bottom. On the other hand, the support structure amplitude is 5 times in operation condition than in parked one. This shows the wind turbine undergoes aerodynamics and mechanical effects in the operation situation.

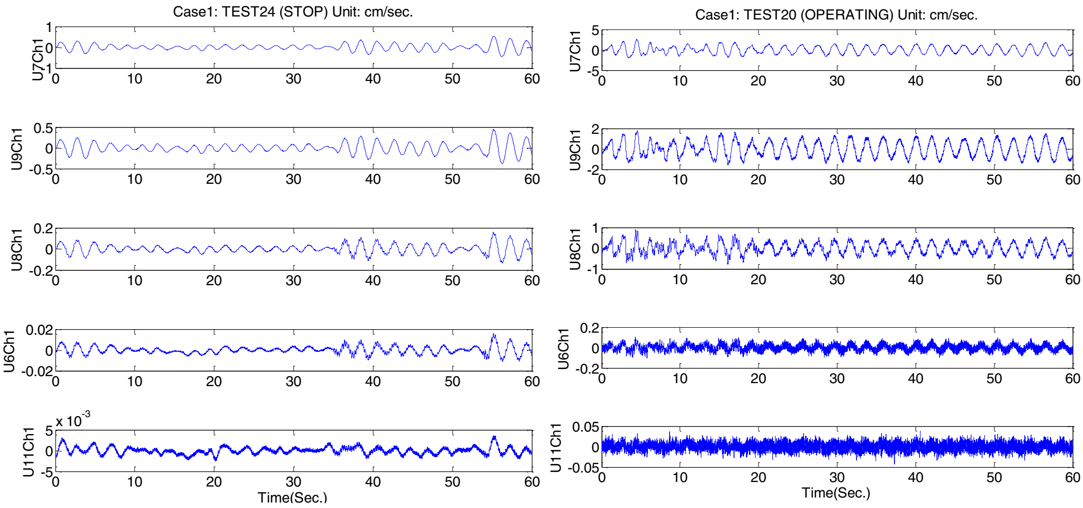


Figure 7: The vibration signals of the wind turbine on the parked and operating conditions.

Two well-developed methods were adopted to obtain the structural dynamic behaviors of the support structure of wind turbine: Direct FFT method, and Frequency Domain Decomposition (FDD).

Direct FFT is a traditional analysis technique. It transfers the structural response signals into frequency domain by Discrete Fourier Transform. The mode shapes could be extracted through picking peak points in the frequency domain and capturing the power and phase values of the spectrum functions to construct the mode shapes.

Frequency Domain Decomposition was developed by Rune Brinker in 2001[5] and is briefly introduced as below. The relationship between the unknown inputs x(t) and the measured responses y(t) can be expressed as [5]

$$\mathbf{G}_{yy}(j\omega) = \bar{\mathbf{H}}(j\omega)\mathbf{G}_{xx}(j\omega)\mathbf{H}(j\omega)^{T} \quad (1)$$

where $\mathbf{G}_{xx}(j\omega)$ is the (r × r) power spectral density (PSD)matrix of the input, r is the number of inputs, $\mathbf{G}_{yy}(j\omega)$ is the (m × m) PSD matrix of the responses, m is the number of responses, $\mathbf{H}(j\omega)$ is the (m × r) frequency response function (FRF) matrix and the overbar and superscript T denote the complex conjugate and transpose, respectively. In order to simplify Equation (1), an assumption of white noise input is required, i.e. $\mathbf{G}_{xx}(j\omega) = C$. Applying Heaviside partial fraction theorem and mathematical manipulation, and in the case of a lightly damped structure, at a certain frequency ω only a limited number of modes will contribute significantly; let this set of modes be denoted by $\mathrm{Sub}(\omega)$. The response spectral density can always be written

$$\mathbf{G}_{yy}(j\omega) = \sum_{k \epsilon \mathrm{Sub}(\omega)} \frac{\mathbf{d}_k \boldsymbol{\Phi}_k \boldsymbol{\Phi}_k{}^T}{j\omega - \lambda_k} + \frac{\bar{\mathbf{d}}_k \bar{\boldsymbol{\Phi}}_k \bar{\boldsymbol{\Phi}}_k{}^T}{j\omega - \bar{\lambda}_k} \quad (2)$$

In the FDD identification, the first step is to estimate the PSD matrix. The estimate of the output PSD $\hat{\mathbf{G}}_{yy}(j\omega)$ known at discrete frequencies ω = ωi is then decomposed by taking the SVD of the matrix

$$\hat{\mathbf{G}}_{yy}(j\omega_i) = \mathbf{U}_i \mathbf{S}_i \mathbf{U}_i{}^H \quad (3)$$

where the matrix$\mathbf{U}_i = [u_{i1} \quad u_{i2} \quad \cdots \quad u_{im}]$ is a unitary matrix holding the singular vectors $u_{ij}$ , and $\mathbf{S}_i$ is a diagonal matrix holding the scalar singular values $s_{ij}$ . Near a peak corresponding to the kth mode in the spectrum this mode, or maybe a possible close mode, will be dominating. If only the kth mode is dominating there will only be one term in Equation (3). Thus, in this case, the first singular vector $\mathbf{u}_{i1}$ is an estimate of the mode shape

$$\hat{\boldsymbol{\Phi}} = \mathbf{u}_{i1} \quad (4)$$

The structural responses in parked condition are analyzed with Direct FFT and FFD method, and the results are shown in **Figure 8** and **Figure 9**.
Through direct FFT method, two featured frequencies can be observed from the fourier spectrum. They are 0.4833Hz、3.85 Hz respectively. And the corresponded mode shapes can be illustrated through the amplitude and phase of the featured frequency point. And the captured first two mode shapes are physicalize matched with the concept of structural dynamic.
**Figure 9** shows the results from the FDD method. By decomposing the peak values through PSD matrix, the singular values are plotted. By observing the peak value of singular value specrum, two peak points can be identified, 0.475 Hz and 3.85 Hz. After the featured frequencies are extracted, the mode shapes could be obtained, too. Comparing the difference between the results from the results of these two methods, their frequency characteristics and mode shapes are highly matched which means the primary modal features are captured successfully.

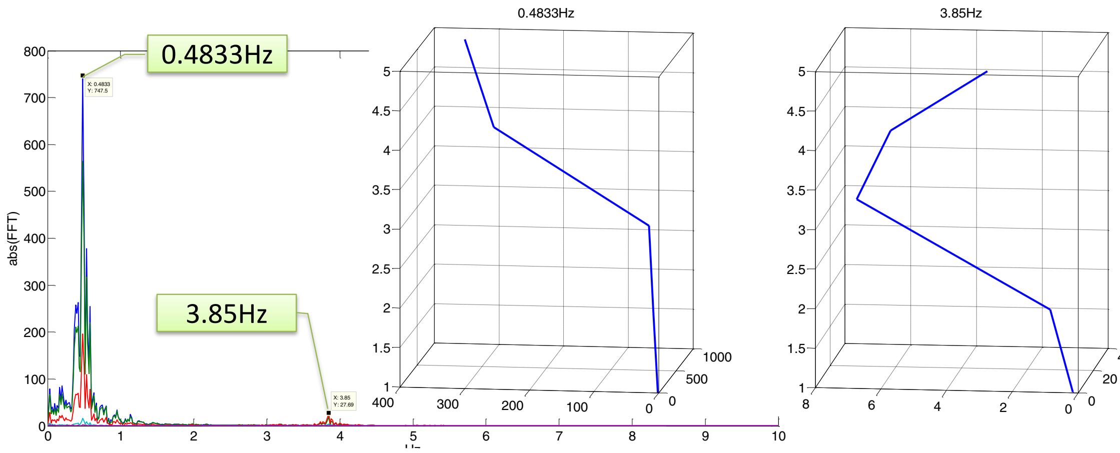

Figure 8: The analysis result of the wind turbine on the parked condition via Direct FFT.

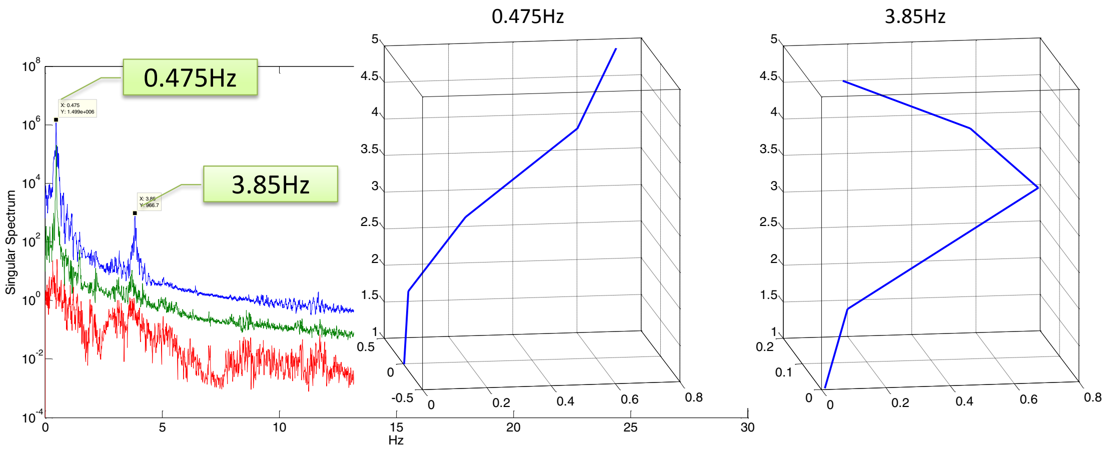

Figure 9: The analysis result of the wind turbine on the parked condition via FDD

## 3 CONCLUSIONS

The structural responses of the on-shore wind turbine (GE 1.5MW) were successfully obtained in this study, and the performance of wireless sensing system (NTU-WSU) was also certified in the wind turbine application. Through FFT observing and frequency domain decomposing analysis, the roughly dynamic behaviors of the wind turbine were extracted in this study. The NTU-WSU provides a effective and low cost way to monitoring and collect the structural responses. Since the measured signals from wind turbines contains lots of forcing and environment effects, such as the aerodynamics, soil-strucutre interaction, and rotoring effects, there are still great efforts in the coming future. To clearly the structural vibration behaviors of wind turbines, in addition to constructing the entire numerical model of wind turbine, the comparisons between model and experiments would be performed.

## 4 ACKNOWLEDGEMENTS

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