Vertical axis wind turbine monitoring using FBG sensors

Bastien Van Esbeen*[a], Valentin Manto[b], Damien Kinet[a], Christophe Caucheteur[a]
[a]ERC Unit – Advanced Photonic Sensors, 31 Bld Dolez, 7000 Mons, Belgium;
[b]Fairwind, 299 Chaussée de Gilly, 6220 Fleurus, Belgium

ABSTRACT

This paper reports experimental results obtained on a fiber Bragg gratings (FBG) system able to sense the deformations of a vertical axis wind turbine (VAWT) tower. Cost and time optimization is paramount in the industry. Therefore, structural health monitoring (SHM) is needed to prevent machines from failure. In this project, three FBG strain sensors are placed vertically along a VAWT tower, each spaced by 1.5 meter. A comparison of every sensor revealed that height has no significant influence on the sensor sensitivity for the first 4.5 meters of the tower. By means of a power spectral density (PSD) applied on the measured signal, three sources of deformation can be retrieved: wind force, blades unbalance and 1st tower mode resonance. Each deformation source is characterized by a specific frequency. The wind force and the blades unbalance induce mechanical stresses at a frequency that depends on the rotational rate. The 1st tower mode only depends on the system geometry, so not on the rotational rate. A qualitative analysis of the deformation amplitude is performed for different rotational rates within the VAWT operational range (10-35 rpm). The results show the deformation amplitude due to the wind force depends on the wind speed which is naturally not predictable. The amplitude for the resonance depends on how close the rotational rate is to the resonant frequency (22 rpm) and on the duration lasted at this rate. For the blades unbalance, the deformation amplitude increases with the rotational rate, due to the centrifugal effect.

Keywords: Fiber Bragg grating, VAWT monitoring, structural health monitoring, fiber optic sensor

1. INTRODUCTION

Wind turbine (WT) Structural Health Monitoring (SHM) is a widespread research domain for onshore WT[1–6] as well as offshore WT[6,7]. Indeed, it consists in a powerful predictive maintenance method with the potential to save a lot of time and money that would be spent in case of failure. So far, the literature mainly focuses on horizontal axis wind turbines (HAWT). Our research targets vertical axis wind turbine (VAWT) monitoring and is a result of a collaboration between the University of Mons and FAIRWIND, a company that designs and produces VAWT, based in Fleurus, Belgium.

In this work, focus is given on VAWT tower monitoring as the design of a system communicating between a rotating part (sensors on blades or struts) and a static one (power supply in electrical cabinet on the floor) is very complex and should be conceived after a good demonstration of tower monitoring. The paper is divided into different parts. First, a brief explanation of the working principle of fiber Bragg gratings (FBG) is given. Then, the sensors design and installation are described. Section 4 relates the analysis and interpretation of the results (influence of the sensor height and determination of the deformation sources). The document ends with the conclusion and perspectives of development.

2. FBG WORKING PRINCIPLE

A fiber Bragg grating is a permanent and periodic modulation of the core refractive index of an optical fiber. This modulation acts as a distributed mirror, reflecting a part of the light at the Bragg wavelength λ_B and transmitting all others. An FBG is characterized by its grating length L, grating period Λ and refractive index modulation δn. The Bragg wavelength λ_B can be computed as

$$\lambda_B = 2(n_{\text{eff}} + \delta n)\Lambda \approx 2n_{\text{eff}}\Lambda \tag{1}$$

*bastien.vanesbeen@umons.ac.be

where n_{eff} is the effective refractive index of the optical fiber core. Any change of n_{eff} or Λ induces a Bragg wavelength shift, which can be used for temperature, axial strain or pressure sensing. The FBG sensitivity to strain and temperature behaves linearly and without hysteresis, typical values are 1.2 pm/µε and 10 pm/°C, respectively.

3. SENSORS DESIGN AND INSTALLATION

The scheme of the VAWT monitored in this work is presented in Fig. 1. The main type of tower deformation is bending, implying vertical strains on the tower sides. In order to measure these deformations, FBGs need to be placed vertically as they only sense axial strain. An investigation of the height influence on the sensor sensitivity is carried out by installing four vertical sensors along the tower, within the same optical fiber. These are separated by about 1.5 m. The first three FBGs are glued to the tower, so they are sensitive to both strain and temperature changes. The fourth one is not stuck so that it is deformation insensitive, this sensor is used for temperature calibration to deduce the strain contribution of the first three FBGs. Strain sensors must be pre-strained when glued to ensure compression sensitivity in addition to elongation. The fiber is placed on the tower side where the prevailing wind comes from, to maximize the sensor elongation due to bending.

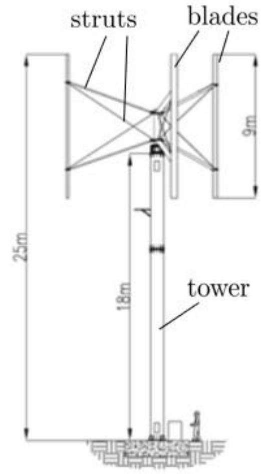

Figure 1. VAWT scheme.

4. MEASUREMENTS AND ANALYSIS

Measurements were done by an FBG interrogator able to record the Bragg wavelengths of the four sensors in the fiber as a function of time. Different rotational rates were imposed to the VAWT generator, from 10 to 35 rpm by steps of 5 rpm. Attention has to be paid to the resonance frequency, namely 22 rpm. Around this rate, measurements must not last too long for safety reasons. Two studies were performed. First, the influence of the height on the sensitivity will be analyzed by comparing the response of each strain sensor at heights of 1.5m, 3m and 4.5m, at given rotational rates. Then, a frequency analysis is applied to the signals to determine the deformation oscillations at stake and deduce their physical origin.

4.1 Height analysis

The goal is to determine whether the sensor position along the tower height has an influence on the sensitivity to deformations. The FBG with the highest sensitivity shows the largest dynamic range, i.e. the difference between the maximum and minimum wavelength shift. When looking at the temporal evolution of the Bragg wavelength shift of the three sensors for every imposed rate, it appears that no sensor is significantly more sensitive. For example, Fig. 2a and 2b show the Bragg wavelength shift versus time of the four sensors, for a few seconds, at rates of respectively 10 and 25 rpm.

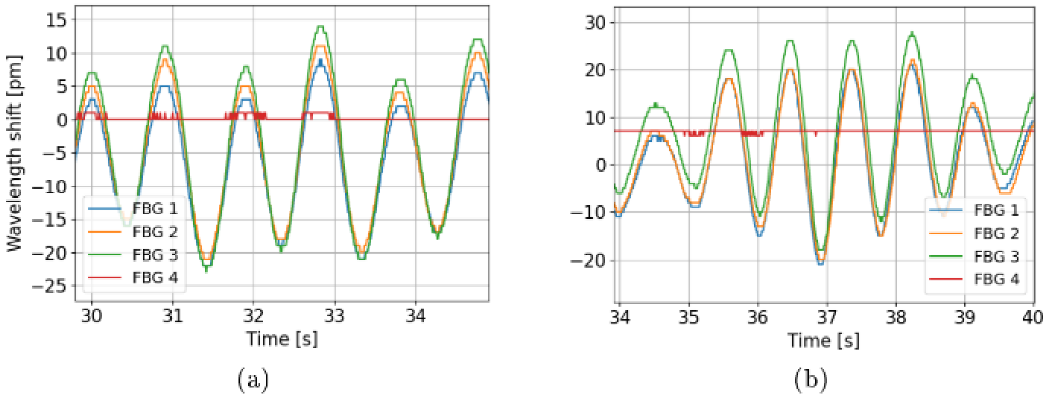

Figure 2. Bragg wavelength shifts versus time for the four FBGs. (a) At 10 rpm. (b) At 25 rpm.

FBG 1, 2 and 3 are the strain sensors while FBG 4 (red curve) represents the temperature evolution. On these graphs, the dynamic range of FBG 3 is slightly larger than the others, so analyses will be done using this sensor. Even if FBG 3 is the highest sensor, this difference is so small that it cannot be considered as the result of a sensitivity dependence on height. Indeed, this could e.g. come from a better gluing process that would transfer more deformation from the tower to the FBG. If the installation systems allow it, it could be interesting to investigate the sensitivity for even higher sensors or to study the sensitivity distribution along the whole height of a miniature model. It can be concluded that, for the first 4.5 meters of the tower, there is no evidence of sensitivity dependence on height.

4.2 Frequency analysis

A power spectral density (PSD) computation is carried out on the wavelength shift evolution of FBG 3 at every rotational rate. The resulting computations at 10, 20, 25 and 35 rpm are presented in Fig. 3. Based on the peaks position and amplitude, three physical phenomena can be distinguished for the deformation origin.

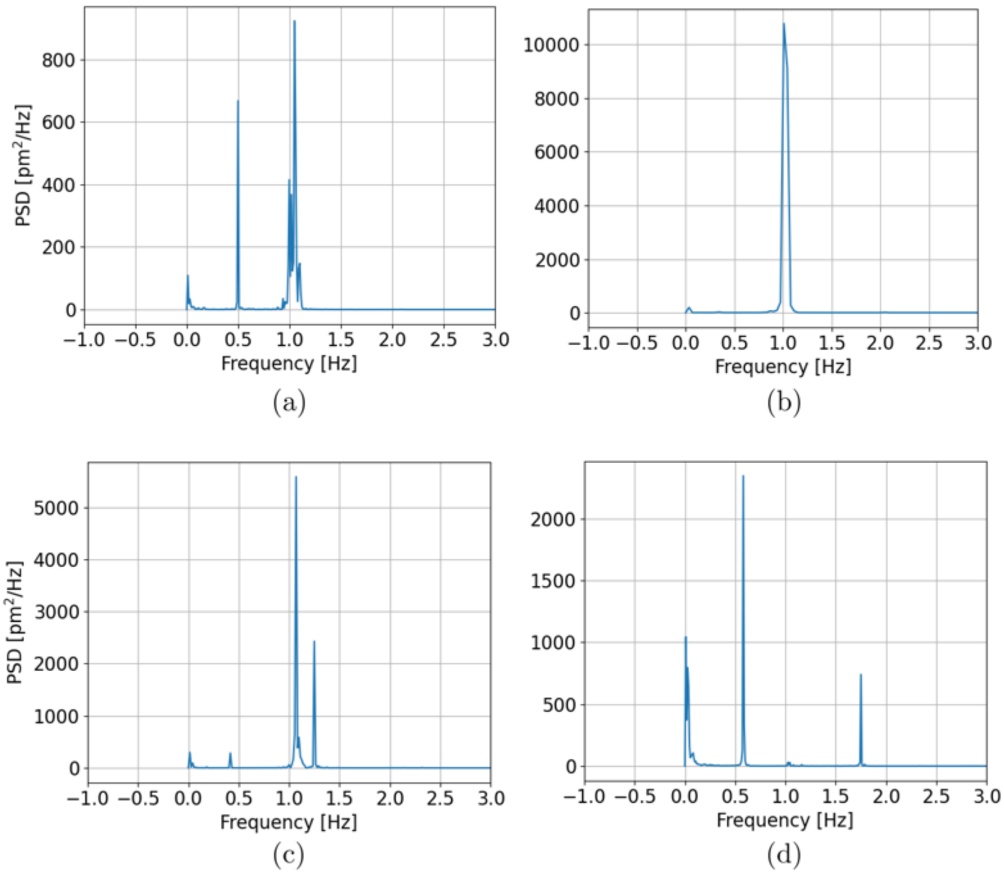

Figure 3. PSD computation of FBG 3. (a) At 10 rpm. (b) At 20 rpm. (c) At 25 rpm. (d) At 35 rpm.

First, the wind force applied to the structure is a source of tower bending. Considering the wind speed constant for one rotation, the force underwent by the WT depends on the blades position. As the WT is composed of three blades, the position repeats thrice per round, therefore this leads to tower oscillations at the passing blade frequency, i.e. $(R/60) \times 3$ Hz with R the WT rotational rate in [rpm]. The deformation amplitude depends on the wind speed.

Secondly, depending on the geometry of the wind turbine, certain modes of resonance can be excited. According to the technical report of the concerned WT from FAIRWIND, the only mode interesting in practice (because it is excited within the WT allowed operational range: $10 - 39$ rpm) is the 1st tower mode that occurs at about 1.1 Hz. If the excitation is ~ 22 rpm, there will be amplification of the 1st tower mode response, indeed 22 rpm is $(22/60) \times 3$ passing blades per second, which is equivalent to a repeated mechanical force at 1.1 Hz. The result is a tower oscillation with an increasing bending amplitude, this is the phenomenon of resonance.

Thirdly, the last main source of tower deformation is due to blades unbalance. Ideally, the WT is perfectly balanced, but some weight differences are unavoidable in practice. As a result, the tower bends in the direction of the heaviest blade, leading to oscillations at the frequency of a same passing blade, so $(R/60)$ Hz. Due to the centrifugal effect, the higher the rotational rate, the higher the force and the more important the deformations. An excitation of 66 rpm would therefore also lead to a 1st tower mode resonance but it is outside of the operational range.

On Fig. 3a (10 rpm), there are peaks at $(10/60) \times 3 = 0.5$ Hz (wind force) and 1.1 Hz (1^{st} tower mode excited because the WT passed through 22 rpm a couple of minutes before the measurement). Fig. 3b (20 rpm) shows one peak around 1 Hz because both peaks at 1 Hz and 1.1 Hz overlap. In Fig. 3c (25 rpm), the effect of the resonance (1.1 Hz) is still important, the wind force implies a component at 1.25 Hz, and a new peak is born at $25/60 \approx 0.42$ Hz, explained by the fact that 25 rpm is large enough to make the centrifugal effect of the blades unbalance non negligible. This effect is even more amplified at 35 rpm, in Fig. 3d ($35/60 \approx 0.58$ Hz), and the component at 1.75 Hz is still present while the resonance has almost completely faded away, as the measurements were taken several minutes after the passage through 22 rpm.

5. CONCLUSION AND PERSPECTIVES

This research is a good basis for VAWT SHM as it demonstrates the ability to determine the importance and the source of bending deformation with a single sensor. In the industry, it has the potential to become a powerful tool for predictive maintenance. The next step is to study more precisely the sensor sensitivity as a function of the height (e.g. thanks to a scale model). Afterwards, measurements will be taken during a normal operation of the WT, not imposing rotational rates. A testing campaign will also be performed without wind to compare the results of the deformation oscillations due to wind force. Moreover, vertical sensors will be installed all around the tower with a goal of determination and study of the tower bending direction. Also, horizontal and oblique sensors could be placed on the WT tower to check if other types of deformation are involved. This would be the basis of a future mechanical efforts analysis from tower deformation according to three axes. Finally, a feasibility study for sensor integration inside the WT before assembly would be interesting to protect the fiber from bad weather.

REFERENCES

[1] Schroeder, K., Ecke, W., Apitz, J., Lembke, E. and Lenschow, G., "A fibre Bragg grating sensor system monitors operational load in a wind turbine rotor blade," Meas Sci Technol **17**(5), 1167–1172, Institute of Physics Publishing (2006).

[2] Park, S., Park, T. and Han, K., "Real-time monitoring of composite wind turbine blades using fiber Bragg grating sensors," Advanced Composite Materials **20**(1), 39–51 (2011).

[3] Kim, S. W., Kang, W. R., Jeong, M. S., Lee, I. and Kwon, I. B., "Deflection estimation of a wind turbine blade using FBG sensors embedded in the blade bonding line," Smart Mater Struct **22**(12) (2013).

[4] Kim, H. il, Han, J. H. and Bang, H. J., "Real-time deformed shape estimation of a wind turbine blade using distributed fiber Bragg grating sensors," Wind Energy **17**(9), 1455–1467 (2014).

[5] Krebber, K., Habel, W., Gutmann, T. and Schram, C., "Fiber Bragg grating sensors for monitoring of wind turbine blades," 17th International Conference on Optical Fibre Sensors **5855**, 1036, SPIE (2005).

[6] Wen, B., Tian, X., Jiang, Z., Li, Z., Dong, X. and Peng, Z., "Monitoring blade loads for a floating wind turbine in wave basin model tests using Fiber Bragg Grating sensors: A feasibility study," Marine Structures **71** (2020).

[7] Mieloszyk, M. and Ostachowicz, W., "An application of Structural Health Monitoring system based on FBG sensors to offshore wind turbine support structure model," Marine Structures **51**, 65–86 (2017).