Bending Monitoring of a Vertical Axis Wind Turbine Tower by Means of FBG Strain Sensors

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Abstract: A vertical axis wind turbine tower was equipped with FBG for SHM. The obtained results explain the deduction of three deformation sources and the most sensitive position of sensors along the tower height was determined.

1. Introduction

Wind turbines undergo a strong and permanent variation of stresses which makes them vulnerable to mechanical fatigue, therefore structural health monitoring is necessary to guarantee the machines integrity. Horizontal axis wind turbines (HAWT) are now widely fitted with strain sensors (e.g. onshore [1–4] or offshore [5,6]) while the case of vertical axis wind turbines (VAWT) is not yet mentioned in the literature. Moreover, fiber Bragg grating (FBG) sensors are more and more considered for SHM due to their various advantages (lightweight, information in wavelength division multiplexing, robustness, electromagnetic immunity…). This work presents the first measurements of VAWT tower bending deformation thanks to FBG sensors. Three strain sensors were installed on a VAWT owned by Fairwind (Fleurus, Belgium), a company that designs and manufactures VAWTs. The paper describes the sensors installation and the measurement method. Afterwards, the obtained results are exposed following two analyses: a preliminary height study for the optimal sensor position and a frequency analysis. The latter provides the deduction of three different tower bending sources. Finally, a scaled setup is mounted to highlight the optimal position of sensors along the tower height, i.e. the most sensitive region for vertical deformations. Future placements will be based on these results.

2. Sensors design and placement

The company Fairwind provided one of their VAWTs, located in Fleurus (Belgium), for the study. This is the model F100-10, as shown in Fig. 1a. As the machine rotation axis is along the tower, it is particularly interesting for this type of wind turbine to focus on bending deformations of the tower (see sketch in Fig. 1b).

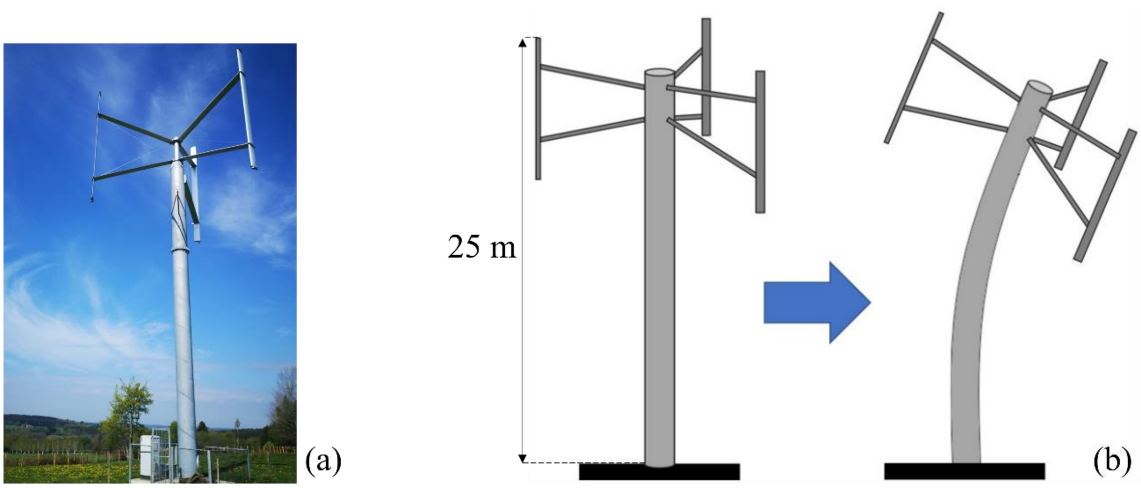

Fig. 1. Vertical axis wind turbine: (a) Picture of the F100-10 model; (b) Sketch of tower bending.

Henceforth, since FBGs are sensitive to axial strain, they must be oriented vertically, indeed bending induces vertical strain on the tower surface. Three FBGs are inscribed within a single optical fiber (single-mode telecommunication-grade) at different wavelengths in the range 1540-1580 nm. Given that FBGs react to both strain and temperature, a fourth FBG is inscribed for the sake of exclusive temperature measurement. The strain contribution of the first three sensors can be retrieved by subtracting the signal of the temperature sensor.

The installation consists of placing the three strain FBGs (bare) at different heights along the tower (1.5 m, 3 m, and 4.5 m from the bottom) with a glue as *Loctite*. The temperature FBG (with a protective sheath) is a bit above 4.5 m and is not glued to ensure insensitivity to strain.

3. Measurements on the VAWT tower

The Bragg wavelength shifts of the four sensors are recorded under a series of conditions: rotational rates are imposed to the VAWT generator from 10 to 35 rpm (rotations per minute) by steps of 5 rpm. Each measurement lasts a few tens of seconds. The particularity of this VAWT is that the resonance frequency (22 rpm) lies within its regular operational range. This specific resonance mode, called 1st tower mode, is detected by the installed FBGs since it generates tower bending oscillations. Between 15 and 20 rpm, measurements are taken by steps of 1 rpm to have a more accurate analysis of the tower behavior approaching the resonance frequency. However, around 22 rpm (between 20 and 25), the transition must be as quick as possible to avoid excessive strain on the machine that could cause mechanical damage.

After signal processing to extract the strain component of the three sensors from the temperature signal, a comparison between them is performed to determine the height that provides the best sensitivity. Afterwards, a frequency analysis is carried out by means of power spectral density (PSD) computations in order to find out at which frequencies the bending oscillations occur.

3.1. Height analysis

For this study, we need to assess the sensitivity of each strain sensor, located at different heights. It means that, for a given set of oscillations, the most sensitive FBG should be characterized by the largest difference between its maximum and minimum. Unfortunately, after analysis of each signal, sometimes the FBG located the highest is the most sensitive, sometimes it is the FBG the lowest, depending on the imposed rotational rate. This preliminary height study being not conclusive, an extensive survey was conducted, the findings of which are set out in section 4.

3.2. Frequency analysis

To each measured Bragg wavelength shift as a function of time, the power spectral density is calculated. For example, considering the signal of the lowest FBG, the PSD in the case of an imposed rotational speed of 10 (resp. 25) rpm can be found in Fig. 2a (resp. 2b).

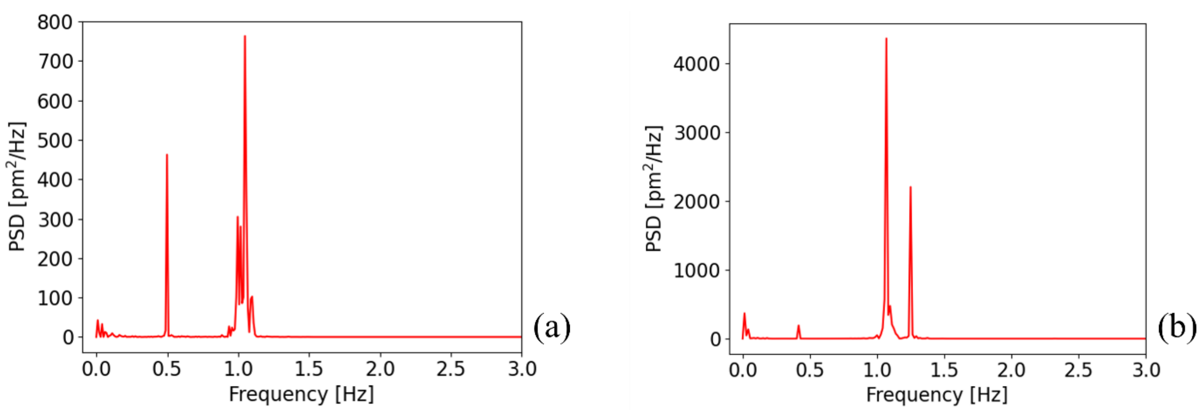

Fig. 2. Power spectral density computation on the measured Bragg wavelength shift of the lowest FBG at a rotational speed of: (a) 10 rpm; (b) 25 rpm.

The observations made from the analysis performed for each imposed rotational rates reveal three sources of tower bending deformation, each featured by a specific frequency. First, the wind applies a force on the wind turbine and mainly on the machine head, implying bending of the tower. Seen from the wind direction, the machine head position repeats thrice per rotation (as it is composed of three blades), so the force applied on the VAWT oscillates at a frequency that corresponds to three times the VAWT rotational speed, i.e. $(V_R/60).3$ Hz with V_R the rotational speed in rpm (rotations per minute). Secondly, regardless of the rotational speed, there are tower bending oscillations at 1.1 Hz. This is due to a resonance mode, called the first tower mode, whose frequency only depends on the machine geometry (1.1 Hz for the F100-10 VAWT model). As mentioned above, the interesting point is that the wind force, coupled with a rotational rate of 22 rpm, excites the first tower mode response, as $(22/60).3 = 1.1$ Hz. Finally, the third source of bending deformation is the structure unbalance. It creates bending oscillations at the VAWT rotational rate, i.e. $V_R/60$ Hz. This effect increases with V_R and can be neglected until 25 rpm.

To apply these observations to the above example, at 10 rpm, the wind force should induce tower oscillations at $(10/60).3 = 0.5$ Hz, which corresponds to the first peak in Fig. 2a. At 25 rpm (Fig. 2b), this peak is now at 1.25 Hz and another little peak has appeared at ~0.42 Hz $(= 25/60)$, as a result of the structure unbalance of which the centrifugal effect becomes non negligible. For both 10 and 25 rpm, one can see the peak at 1.1 Hz due to the first tower mode response. This peak is much higher at 25 rpm than at 10 rpm given that the excitation of 22 rpm happened shortly before.

4. Extensive study of sensitivity dependency on height

In this section, a survey about the optimal position for sensor placement along the height of a VAWT tower is carried out on a miniature model in our lab, shown in Fig. 3. The aim of the study is to install sensors on the model and to characterize their sensitivity when applying a bending on it. This miniature model consists of an aluminum bar screwed vertically on a fixed platform at one end and free to move at the other end. An optical fiber in which five FBGs are inscribed, 0.14 m away from each other, is installed along the 0.745m-long bar. The gratings are glued on its surface in such a way that the highest FBG is 0.05 m under the top of the bar, i.e. at a 0.695 m height, and the other ones at 0.555, 0.415, 0.275 and 0.135 m heights. The aluminum bar bending is applied by a dynamometer fixed to a support setup supposed to be immobile (ideally the deformation induced by the applied force should entirely be undergone by the aluminum bar), so that the applied charge is known.

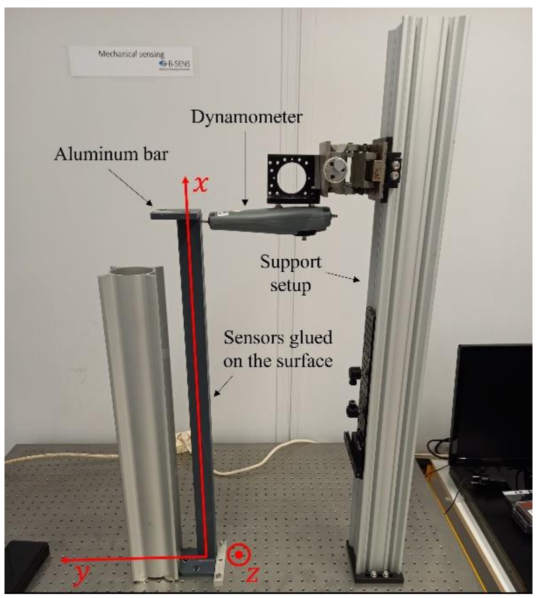

Fig. 3. Picture of the miniature setup for bending test (coordinate system defined in red).

As represented in Fig. 3b, the bar height is along the x-axis and the applied charge along the y-axis. According to the resistance of materials theory, we know that in the case of simple plane bending, the elongation of longitudinal elements at the beam surface is proportional to the normal stress σ given by:

$$\sigma = \frac{M_z y}{I_z} \tag{1}$$

with M_z the bending moment and I_z the moment of inertia, according to the z-axis. The bending moment M_z along the height x is $P(L - x)$, P being the applied load at the free end and L the bar length. The sensors, placed on the surface at $y = -a/2$, with a the width of the square section of the aluminum bar, sense the relative elongation ϵ proportional to σ by the relationship:

$$\epsilon = -\frac{\sigma}{E} \tag{2}$$

where E is the Young's modulus of the material. Therefore, one can conclude that:

$$\epsilon = \frac{P(L-x)a}{2EI_z} \tag{3}$$

As the behavior of the Bragg wavelength shift according to the relative elongation is linear, one can conclude that it is proportional to $P(L-x)$, the other parameters being constants. Several tests were performed for different values of P, where the measured Bragg wavelength shift should be linearly decreasing as a function of the height. Fig. 4 depicts the Bragg wavelength shift of the five sensors positioned at different heights for a load of 500 N. For redundancy, the experiment was repeated 15 times. The linear regression is the green line and is characterized by an R^2 value of 0.998, demonstrating the good linearity of the Bragg wavelength shift according to the height. This observation is applicable for every load value.

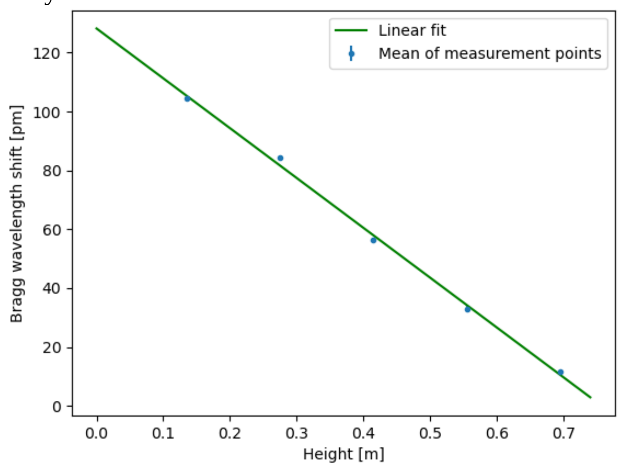

Fig. 4. Bragg wavelength shift [pm] of the five sensors versus height [m] of the aluminum bar with a linear regression.

Even though a VAWT tower is different from this aluminum bar in terms of size and material, this behavior remains valid as the only parameters at stake are E (material) and I_z (size) and would just take other constant values. The conclusion of this study is that the optimal sensor position for bending sensing is at the bottom of the VAWT tower, as it provides the highest Bragg wavelength shift.

4. Conclusion

In this work, FBG sensors were placed along the height of a VAWT tower, and a frequency analysis on the measured signals helped to determine three bending sources: wind force, 1st tower mode resonance and structure unbalance. Based on these sensors, a first height study was not conclusive, so a second extensive study was conducted on a miniature model in the lab, leading to the conclusion that the FBGs should be installed at the tower bottom to ensure the maximum sensitivity.

Future works will investigate the tower bending direction, by installing new sensors vertically all around the tower. Also, a validation of the bending sources hypotheses is planned by leading test campaigns with and without wind and by studying the tower response at several durations after a passage through the resonance frequency.

5. References

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