A Robust Algorithm to Detecting Wind Turbine Blade Health Using Vibro-Acoustic Modulation and Sideband Spectral Analysis

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Abstract Submission for the 33rd ASME Wind Energy Symposium
Abstract

This paper presents a robust crack detection algorithm for wind turbine blades using vibro-acoustic modulation and the area under the curve of the frequency spectrum of the sidebands. In a previous paper it was shown how the operational vibration of the turbine could be used as a pumping signal in vibro-acoustic modulation. However, the sources of the operational vibration frequencies are many and may change over time due to the change of the wind speed, direction and many other factors. Instead of trying to identify peaks in the spectrum of the sideband (a procedure that is error prone), the area under the curve of the sidebands around the probing signal is obtained. Utilizing the area under the curve allows the consideration of multiple operational vibration frequencies simultaneously in the analysis, making the algorithm more robust. By obtaining data simultaneously in all the turbine blades, the same operational vibration frequencies are applied to all blades. The area under the curve of the spectrum of the sidebands is then obtained and compared. If a large discrepancy exists in the area under the curve of the sidebands among the blades, then a potential crack is detected and signaled. In this paper the algorithm and its implementation are described in detail.

Background

Wind power is considered by many to be the most competitive source of renewable power. However, due to the high investment cost it is important to continuously monitor the health of the wind turbine and reduce the cost of unscheduled maintenance [1-2]. Additionally, the failure of a blade can cause damage in other subsystems and neighboring facilities [3]. Detecting early failure in wind turbines is very important to protect the investment cost of the wind farm.

In this paper, a robust algorithm for crack detection is demonstrated using Vibro-Acoustic Modulation. In previous papers [4-5] it was shown how to use Vibro-Acoustic Modulation to detect cracks in turbine blades using a probing signal ($F_{prob}$) and a pumping signal ($F_{pump}$). A probing frequency such as a sine signal is introduced in the blade using a Micro Fiber Composite (MFC). In operational conditions, the wind turbine will produce a lower natural frequency called the pumping signal due to the rotation or the natural frequency response of the rotor and blades. Due to the nonlinearity introduced by a crack, modulation will occur at the probing frequency producing sidebands at $F_{prob} + F_{pump}$ and $F_{prob} – F_{pump}$. These sidebands will be accentuated in the cracked blade due to the nonlinearity introduced by the cracked blade.

Unfortunately, there are many sources of pumping frequencies that are not fixed and may change over time due to different factors such as:

- The different modes of the turbine blades.
- The rotational speed of the rotor.
- The aerodynamic loading and how it causes deformations in the blades.

These aspects make it difficult to identify a single peak for $F_{pump}$ that can be analyzed. Instead of looking for a single $F_{pump}$ peak, all $F_{pump}$ sources are considered in the analysis by integrating the
area in the spectrum over the range where these sidebands are likely to appear \( (F_{\text{pump}_{\text{min}}} , F_{\text{pump}_{\text{max}}}) \).

\[
\text{Area} = A1 + A2 = \int_{F_{\text{prob}} - F_{\text{pump}_{\text{min}}}}^{F_{\text{prob}} + F_{\text{pump}_{\text{max}}}} |\text{FFT}(f(t))| \, df + \int_{F_{\text{prob}} - F_{\text{pump}_{\text{min}}}}^{F_{\text{prob}} + F_{\text{pump}_{\text{min}}}} |\text{FFT}(f(t))| \, df
\]  

(1)

In Figure 1, two pumping frequencies are shown as sidebands of the probing frequency. Instead of trying to identify a single peak, the area under the curve of all the side band frequencies is computed. The area under the curve of the sidebands for all the blades is then calculated. Since the blades have the same structural properties and they are subject to the same operational frequencies, the area under the curve for each blade will be very similar. If they are different by some predetermined factor \( \varepsilon \), then a crack is detected in one of the blades.

**Figure 1** – Based on Vibro-Acoustic Modulation, the entire area under the curve is calculated at the locations of the sidebands of the probing frequency in order to determine whether or not a blade is cracked

**Experimental results**

The wind tunnel used in the experiment consists of six industrial fans pulling the air through a honeycomb material to achieve uniform flow at the inlet to the rotor. A 900-Watt wind turbine, Whisper 100 manufactured by Southwest Windpower, was used for the tests. The diameter of the turbine rotor is 2.1m and the rotor contains 3 blades. Two healthy blades (Blade 2 and Blade 3) and a damaged blade (Blade 1) were used. Figure 2 shows the Fast Fourier transform (FFT) of the data when using a probing frequency of 8000 Hz and 10,000 Hz. There are many sidebands
around the probing frequency and therefore it is difficult to identify their sources. Instead, the area under the curve is calculated for the FFT at the sidebands for each blade and compared. Both graphs show that the area under the curve is larger for the damaged blade (Blade 1).

![Figure 2 – Fast Fourier transform of Whisper 100 blades while in operation for probing frequencies of 8000 Hz (a) and 10,000 Hz (b). The cracked blade is shown in blue.](image)

**Acknowledgements.** Support for this work is provided by the National Science Foundation under grant CNS 1136045.

**Bibliography**


