Crack detection technique for operating wind turbine blades using Vibro-Acoustic Modulation

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ABSTRACT

This paper presents a new technique for identifying cracks in wind turbine blades undergoing operational loads using the Vibro-Acoustic Modulation technique. Vibro-Acoustic Modulation utilizes a low frequency pumping excitation signal in conjunction with a high frequency probing excitation signal to create the modulation that is used to identify cracks. Wind turbines provide the ideal conditions in which Vibro-Acoustic Modulation can be utilized because wind turbines experience large low frequency structural vibrations during operation which can serve as the low frequency pumping excitation signal. In this paper, the theory for the vibro-acoutstic technique is described and the proposed crack detection technique is demonstrated with Vibro-Acoustic Modulation experiments performed on a small Whisper 100 wind turbine in operation. The experimental results are also compared with two other conventional vibro-acoustic techniques in order to validate the new technique. Finally, a computational study is demonstrated for choosing a proper probing signal with a finite element model of the cracked blade to maximize the sensitivity of the technique for detecting cracks.

Key words: Vibro-Acoustic Modulation, crack detection, MFC, nonlinear method, frequency response function, wind turbine blades

CHAPTER 1. INTRODUCTION

Wind power is considered by many to be the most feasible renewable power source due to its competitive energy cost compared to other options, including solar power. For this reason, the wind power industry has grown rapidly in recent decades [1][2]. As wind turbines have been installed and operated, economic data has shown that maintenance costs consume a significant portion of the total energy costs, which are borne by wind farm owners/operators [3][4]. In particular, wind turbine blades require a robust structural health monitoring strategy because the blades are key elements of wind turbines, cost up to 20% of the total turbine cost [2], and are exposed to many unexpected events such as lighting, storms, and extreme winds. Moreover, a failure of the wind turbine blades can lead to failures of other subsystems in the turbines such as the tower, drive train, as well as neighboring infrastructures around the turbine [1]. Therefore, detecting damage before catastrophic failure can help to minimize unscheduled maintenance of wind turbines, which is typically more costly than scheduled maintenance.

The maintenance of wind farms involves several challenges due to trends in wind turbine technology. First, the size of utility scale wind turbines has increased significantly. The wind turbine industry continues to develop larger wind turbines to increase the efficiency of power harvesting. This trend has continued for several decades, and there are plans to install a 8 MW wind turbine which has 164 meter rotor diameter in 2014 [5]. Considering that the span of the wing in the Airbus 380, among the largest aircraft, is 80 meters, wind turbines are the largest aerodynamic structures in the world. This large size causes difficulties for maintaining the wind turbines since repair technicians must climb the towers atop which blades and nacelles are installed. In addition, the speed of a large wind turbine blade at the tip can be up to 370 km/h [6]. It can be dangerous for wind turbine repair technicians to safely approach the wind turbine and several accidents have been reported in recent years. Second, many wind turbines are being built in geographic locations where the wind resource is abundant, and these locations are often difficult for maintenance crews to reach. Many wind turbines have been built on mountains and offshore, and these locations dictate higher costs as it becomes more difficult for construction and maintenance crews to access the turbine. To address these challenges, the development of an efficient maintenance strategy is needed.

This paper focuses on the development of an autonomous crack detection technique. Cracks in wind turbine blades are a structural concern if they initiate in fatigue critical areas due to the cyclic gravitational bending, shear, and axial loading together with the centrifugal loading, and cracks also offer a pathway for moisture intrusion, which can lead to other issues. The proposed technique is based on Vibro-Acoustic Modulation, which measures the response of the blade to two excitation signals with different frequencies. If the blade is cracked, the response will contain nonlinear characteristics that can be quantified to identify the presence of damage. There are several benefits of using Vibro-Acoustic Modulation for crack detection on wind turbine blades. First, Vibro-Acoustic Modulation is a nonlinear crack detection technique; therefore, the sensitivity of this technique to cracks is much higher than linear vibration-based techniques [7]. Next, past studies have reported that Vibro-Acoustic Modulation can effectively detect cracks in structures that are fabricated using various materials including composite materials, which are used to manufacture wind turbine blades [8][9]. Lastly, this technique is less affected by varying environmental and loading conditions [10], which is helpful for structural health monitoring of wind turbines because these turbines operate continuously under a wide range of conditions.

The new technique proposed in this paper utilizes the structural vibration of the turbine blades during operation as the low-frequency pumping signal for Vibro-Acoustic Modulation. By using the vibration that is present during normal operation, the size and weight of the health monitoring hardware is reduced. Furthermore, the use of structural vibrations of the wind turbine blades as the pumping signal enables crack detection when wind turbines are in operation whereas many current wind turbine structural health monitoring techniques must be performed when the turbine is offline.

In this paper, a theoretical review of Vibro-Acoustic Modulation is described and the proposed crack detection method is experimentally demonstrated. Two conventional Vibro-Acoustic crack detection tests were also conducted to validate the proposed method. Finally, a computational study with a finite element model of wind turbine blades is conducted and the results of this study can be used to determine the most sensitive probing excitation frequency for crack detection.

CHAPTER 2. THEORETICAL REVIEW

Vibro-Acoustic Modulation is one type of crack detection technique. It has been demonstrated in the literature that certain kinds of defects in materials such as cracks increase the nonlinear behavior of the material [11]. When the blade material is damaged, the integrity and stiffness of that material changes thereby causing a nonlinear vibrational response. Therefore, by measuring the increase in nonlinearity, damage in the specimen can be ascertained.

The Vibro-Acoustic Modulation test measures the vibrational response of the specimen when it is excited by two sinusoidal signals at different frequencies. These signals are called the pumping signal and the probing signal. The pumping signal is produced at a low frequency called the pumping frequency, f_{pu}, and the probing signal is produced at a high frequency defined as the probing frequency, f_{pr}.

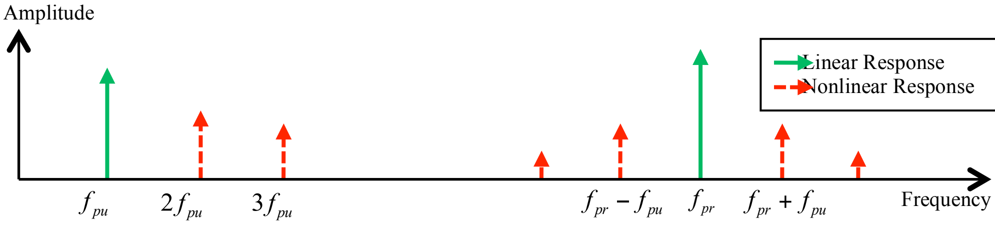


Figure 1. Response to two excitation signals

Figure 1 shows the response when the two excitation signals are theoretically applied to a system. If the system is linear and damped, the response in the steady state is the linear superposition of the responses of each signal and only the linear components of Figure 1 will appear in the frequency spectrum of the response. When cracks cause nonlinear behavior within the system, the response contains both the probing frequency and the pumping frequency in addition to other frequency components such as harmonics of each signal and sidebands around the probing signal. When the system is nonlinear, the stress-strain relationship can be expressed as follows:

$$\sigma = E(\varepsilon + \beta_1\varepsilon^2 + \beta_2\varepsilon^3 + \cdots); \quad E(\varepsilon + \beta_1\varepsilon^2) \tag{1}$$

where σ is the stress, ε is the strain, E is Young's modulus, and β_1, β_2 are nonlinear coefficients. When the strain contains two signals at two different frequencies, the strain can be expressed as follows:

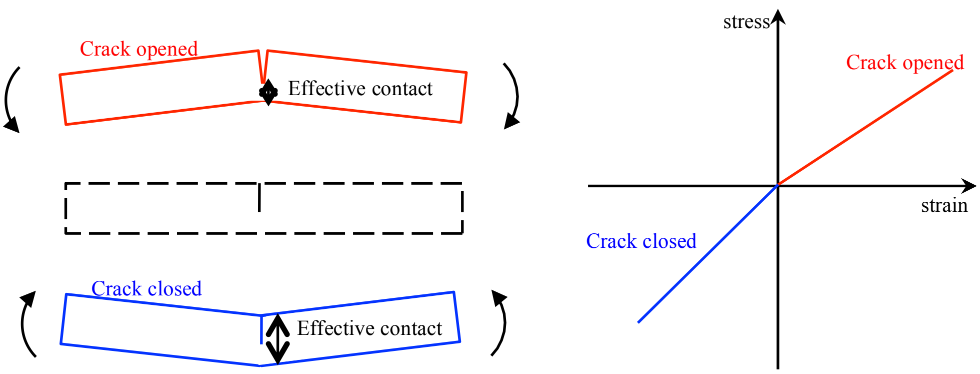
$$\varepsilon = e_{pu}\sin\omega_{pu}t + e_{pr}\sin\omega_{pr}t \tag{2}$$

where $\omega_{pu} = 2\pi f_{pu}$ and $\omega_{pr} = 2\pi f_{pr}$.

The stress is then expressed as

$$\begin{aligned}\sigma &= E(e_{pu}\sin\omega_{pu}t + e_{pr}\sin\omega_{pr}t)\\ &+E\beta_1\left(\frac{e_{pu}{}^2 + e_{pr}{}^2}{2} - \frac{e_{pu}{}^2}{2}\cos 2\omega_{pu}t - \frac{e_{pr}{}^2}{2}\cos 2\omega_{pr}t\right)\\ &-E\beta_1 e_{pu}e_{pr}(\cos(\omega_{pr}+\omega_{pu})t - \cos(\omega_{pr}-\omega_{pu})t)\end{aligned} \tag{3}$$

The first term contains the linear response components and these are the only components that linear systems exhibit. The components in the second term contain frequencies of $2\omega_{pu}$ and $2\omega_{pr}$ which are forced harmonics. The third term contains frequencies of $\omega_{pu} \pm \omega_{pr}$ which are called modulation sidebands. The $\omega_{pu} \pm \omega_{pr}$ components can be further expanded into $\omega_{pu} \pm n\omega_{pr}$ (where n =1, 2, 3, …) components when higher order nonlinear terms are considered. Vibro-Acoustic Modulation elicits these modulation sidebands components at $f_{pr} \pm nf_{pu}$. Since nonlinearities due to defects in the system are not limited to quadratic types of nonlinearities, 2nd and 3rd order sidebands can also be observed.



(a) (b)

Figure 2. (a) Change of effective contact area during crack opening and closing.
(b) Nonlinear stress-strain function.

The mechanism of how a crack increases the nonlinear behavior is not clearly understood. However, there are several explanations which suggest why a crack introduces nonlinear behavior. An intuitive explanation for understanding the relationship between the crack and nonlinearity in the system is the opening and closing action of the crack, or equivalently the change in contact stress along the interface of the crack as a function of load. When the specimen is excited by the pumping signal the crack in the specimen opens and closes according to the period of excitation. The stiffness changes due to the change in contact stress when the crack opens, which introduces nonlinearity into the specimen response because the effective contact area changes (Figure 2(a)). Figure 2(b) shows a nonlinear function in the stress-strain relationship based on the opening and closing effect of the crack. This function is linear when the strain is either positive or negative. However, this function cannot be expressed as a linear function because its slope is discontinuous at the zero strain point.

A Whisper 100 wind turbine manufactured by Southwest Wind Power was used for the experiments in this paper. The Whisper 100 generates 900Watts at 12.5 m/s of approaching wind speed [12] and this turbine model was installed on a tower with a height of 1.626 meters.

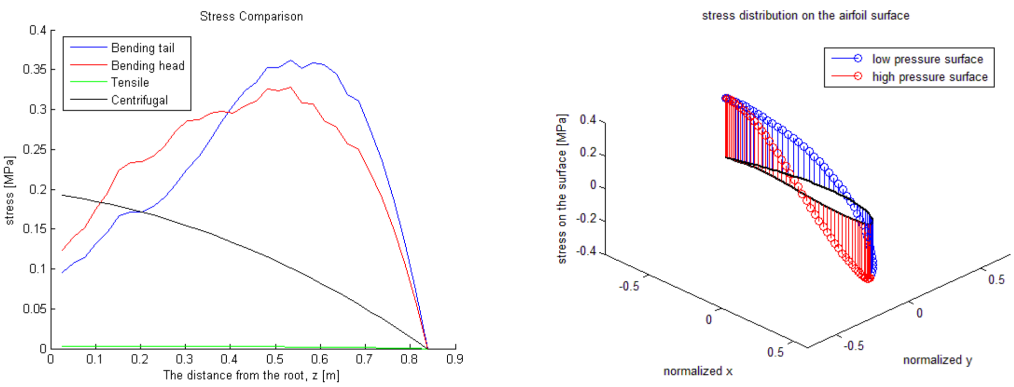
To produce operating conditions of the wind turbine, a wind tunnel was built as shown in Figure 3(a). The wind tunnel consists of six industrial fans at the outlet, a polycarbonate enclosure, and polycarbonate honeycomb at the inlet. The six industrial fans are controlled by an industrial motor controller and the air flow created by the six fans produces wind in the wind tunnel. The dimensions of the wind tunnel are 4.089 X 3.175 X 12.954 meters (Width X Height X Length). These dimensions were selected to reduce the effects of walls of the tunnel on the aerodynamic phenomena. The wind turbine was positioned at 2.4 meters from the end of the wind tunnel downstream where the fans are located.

The rotor of the wind turbine carries three carbon-reinforced fiberglass blades and its rotor diameter is 2.1 meters. In the experiments presented in this paper, one damaged blade and two healthy blades were installed.

Two Micro Fiber Composite (MFC) transducers [13] were installed on each blade- one for the probing excitation and the other for sensing as shown in Figure 3(b). A Micro Fiber Composite (MFC) consists of rectangular piezo ceramic rods sandwiched between layers of adhesive, electrodes and polyimide film. The electrodes are attached to the film in an interdigitated pattern which applies voltage directly to and from the ceramic rods. It is a low profile tranducer that can actuate as well as sense vibration as the transducer expands, bends, or twists. By using these low profile and lightweight MFCs, the effect of the experimental setup on the aerodynamic performance of the blade was minimized.

(a) (b)

Figure 3. Experimental setup for Vibro-Acoustic Modulation tests.
(a) Whisper 100 wind turbine in the wind tunnel. (b) Sensors and actuator installed on the blade.



(a) (b)

Figure 4. Stress distribution on the blade. (a) Stress distribution along span direction.
(b) Stress distribution on a cross-section airfoil surface.

The blades for the Whisper 100 are made of carbon-reinforced fiberglass. However, none of the material properties of the blades were provided by the manufacturer. The material properties such as Young's Modulus (4.847 GPa) were measured from tensile tests performed on the specimens taken from the blades. The measured material density for the blades was 1064 kg/m^3.

To maximize the nonlinear behavior of the blade, the location of the crack was carefully chosen such that the dynamic stress on the blade in operation is the maximum at the crack. In previous studies [14][15][16], it was shown that alternating bending stress due to gravity is the major source of vibration of wind turbine blades in operation. Therefore, only the vibration due to the gravitational force of the blades was considered as the source of dynamic stress in operation.

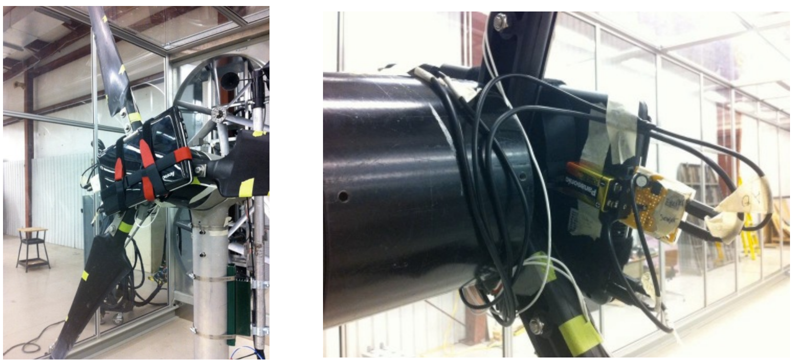
Figure 4(a) shows the dynamic stress distribution along the span direction of the blade while in operation. A theoretical centrifugal force acting at the frequency of 3Hz was plotted for comparison. The stress caused by bending is much larger than tensile or shear stress as commonly shown in other beam structures. The bending stress is even larger than the centrifugal force over most of the range.

Figure 4(b) shows the stress distribution in the cross section of the blade in which the highest stress is caused by bending. Due to the twisting angle, the local maximum points may not exactly be the leading and trailing edges. However, because the twisting angle is small enough in this cross section, the leading and trailing edges are local maxima in the cross-section in this case.

This result also indicates that the Vibro-Acoustic Modulation method should be sensitive to cracks along the trailing edge of the airfoil near the mid-span area of the blade. This characteristic sensitivity corresponds well with reports that blades often fail in the mid-span area of the blade [2]. Another noticeable feature in this result is that a crack located at points where the dynamic strain is large will grow more rapidly under fatigue loading. In other words, cracks that are not as easily detected using Vibro-Acoustic Modulation should be less likely to grow under fatigue (periodic) loading than the cracks that can be detected. This stress distribution can be useful for pinpointing the location of the crack with modal analysis after the existence of damage is verified.

Based on this result, the trailing edge of the blade at 0.3048 meters from the tip of the blade was chosen for the crack location where the maximum stress occurs as shown in Figure 4(a). The crack was induced by applying a sudden load to the tip while the blade was clamped at the intended crack location.

As shown in Figure 5, a wireless data acquisition system was installed on the rotor to eliminate the need to use a slip ring to transmit the MFC signals because slip rings can be susceptible to electrical noise. The data acquisition system includes a small netbook with software that generates the probing signal and acquires the response data, as well as an amplifier, which is powered by a 9-Volt battery. This system provided signals with good signal to noise ratios, despite the 60 Hz noise from the electric power system in the laboratory where the experiments were conducted. The laptop installed on the rotor was controlled remotely by another computer off the turbine which transferred the acquired data.



(a) (b)

Figure 5. Data acquisition system (a) Netbook installation on the hub.
(b) Amplifier installation on the hub.

Three different types of Vibro-Acoustic Modulation tests were conducted on the wind turbine blades to validate the idea of utilizing the structural vibration of wind turbine blades as a pumping signal. First, Vibro-Acoustic Modulation tests were performed on the operating wind turbine blades, the method proposed in this paper. Next, Impact Modulation tests and conventional Vibro-Acoustic Modulation tests using two actuators were conducted for comparison.

4.1 Vibro-Acoustic Modulation Tests in Operation

Vibro-Acoustic Modulation tests were conducted on the wind turbine operating in the wind tunnel. While the wind turbine was rotating, a MFC actuator attached on the blade was excited and another MFC sensor on the blade was used to measure the response of the blade. The sampling rate was 96 kHz and the measurement period was 5 seconds. The rotational speed of the wind turbine was 3.0 ~ 3.2 Hz. Sinusoidal probing signal excitations for the MFC actuator at frequencies of 5 kHz - 10 kHz were used. The acquired data was transformed using a discrete Fourier Transform with a Hanning window and the sideband levels at $f_{pr} \pm f_{pu}$ were observed in the frequency spectrum.

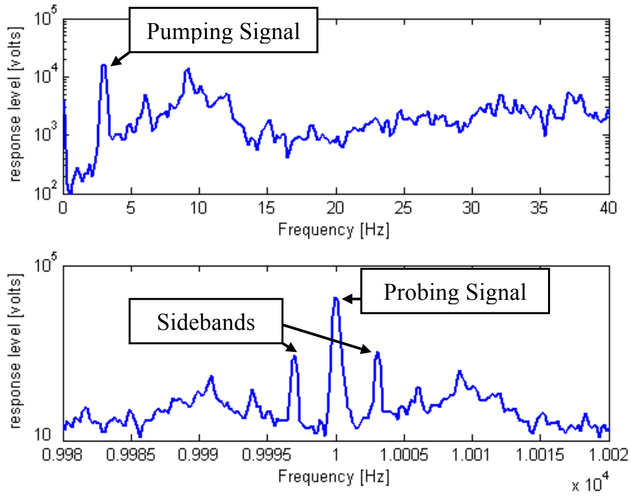


Figure 5. Vibro-Acoustic Modulation test result on the damaged blade.

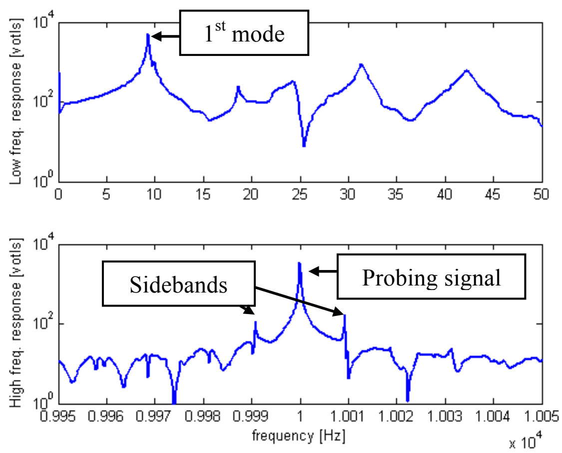


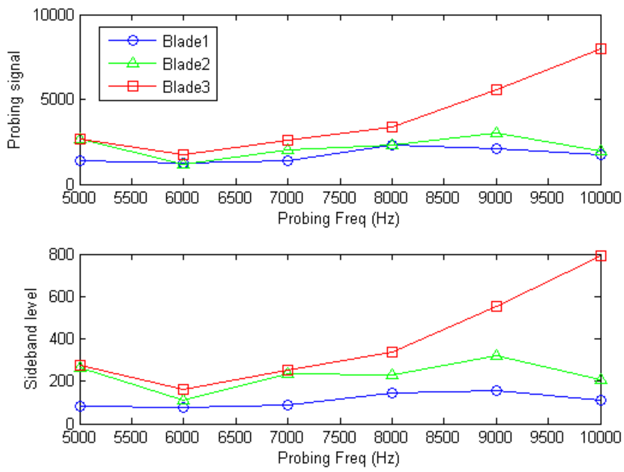
Figure 6. Impact modulation test result.

Figure 5 shows one of the response spectra acquired in the tests. The peak at 3.1 Hz is the rotational speed of the rotor and was observed in the low frequency range with its 2nd and 3rd harmonics. This signal provided the pumping signal for the Vibro-Acoustic Modulation tests. Around the peak at the probing frequency, the sideband peaks due to the modulation with this pumping signal are observed at $f_{pr} \pm f_{pu}$.

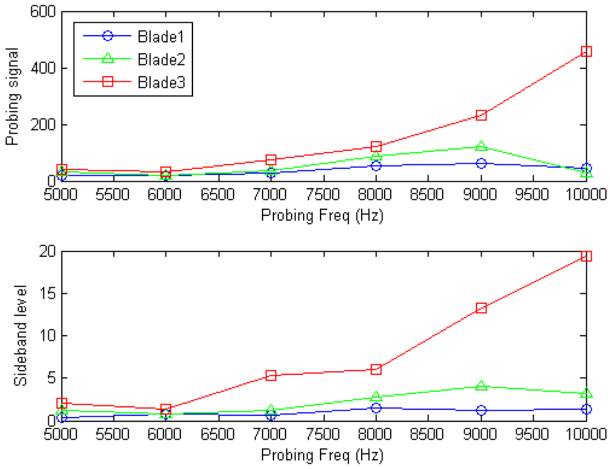
In addition to the sidebands at the specified frequency of $f_{pr} \pm f_{pu}$, most of the low frequency components were also present on both sides of the peak at the probing frequency. Therefore, it can be concluded that most of the low frequency components modulated the probing signal. This conclusion implies that any vibrational components at low frequencies can be utilized as a pumping signal. For the tests conducted in the wind tunnel, the excitation at 9.4 Hz was particularly effective as a pumping signal because it was not only the third harmonic of the rotational speed of the blade, but it was also near the first natural frequency of the blade; thus the sidebands at $f_{pr} \pm 9.4$ Hz are relatively strong.

Some researchers have reported that the sideband level acquired from Vibro-Acoustic Modulation tests varies by probing frequency [17][18]. Therefore, Vibro-Acoustic Modulation tests on the operating wind turbine were conducted using several different probing frequencies. Figure 7(a) shows the measured amplitudes of the sidebands and the amplitude of response at the probing frequency. The sideband levels plotted on this figure were calculated from the sum of the sideband amplitudes at $f_{pr} \pm f_{pu}$. Note that only blade 3 is damaged and the other two blades do not contain cracks. It can be seen that stronger sidebands were observed for the damaged blade at some of the probing frequencies. However, the healthy blades also have relatively strong sidebands. There could be several possible reasons for this difference. First, the blade material itself can exhibit nonlinearity as shown in the tensile tests of the specimens taken from the blades[16]. Another possible source of nonlinearity is the boundary conditions of the blades. The root of the blade is clamped on the nacelle by bolts, and it has been reported that bolts often cause nonlinearities [19]. Other joints between the parts of the wind turbine structure such as the tower, foundation, and rotor can cause nonlinear responses as well. While all these other factors can cause nonlinearities, they should be fairly constant across the blades. Therefore, if one measures a much larger modulation in the damaged blade than in the healthy blades, one can assume an increase in the sideband amplitudes is correlated with the presence of the crack.

It is also important to note that the curves of the response at the probing frequency and the curves of the sideband level are very similar. It is thought that the sideband levels are affected by similar values of the frequency response function of the specimen because the frequency difference between the probing frequency and sideband frequencies is very small.



(a)



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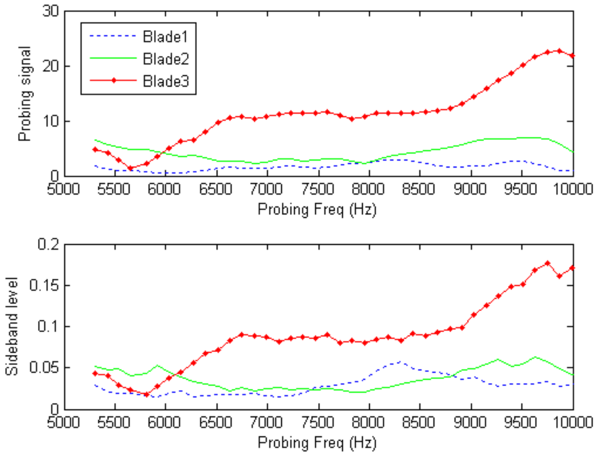

(c)

Figure 7. Result of Vibro-Acoustic Modulation tests with different probing frequencies.
(a) Vibro-Acoustic Modulation test result in operating conditions.
(b) Impact modulation test result. (c) Conventional Vibro-Acoustic Modulation test result.

4.2 Impact Modulation Tests

The Impact Modulation test is a nonlinear defect detection technique that uses free vibrations at the natural frequencies (excited by an impact) as the pumping signal [20]. One of the major benefits of impact modulation testing is that the impact can produce a large amplitude pumping signal. In this test, the tips of the blades were impacted to excite the first modes of vibration of the blades in flapping motion rather than by operating the turbine. The probing signal was excited by the MFC transducer. The tests were performed using the same probing frequencies used in the Vibro-Acoustic Modulation test in operation.

Figure 6 shows the frequency spectrum of the response. The feature shown in the low frequency range is the frequency response function of the blades between the impact point and the sensor. The impact excited a broadband of response frequencies in the low frequency range. It is also interesting to compare the low frequency response in Figure 6 with Figure 5. The curve at 0~20 Hz in Figure 6 is similar to that in Figure 5. Since the third harmonic in Figure 4.1 is located at the natural frequency of the blade, it has a larger amplitude than the second harmonic and almost the same amplitude as the pumping signal. The first natural frequency of the blade was approximately 9.4 Hz.

The free vibration at this frequency was used as the pumping signal in this Impact Modulation test. The measured probing signal response and sideband responses are plotted in Figure 7(b). Even though the pumping signal was different from that used in the Vibro-Acoustic Modulation tests in operating conditions, the sideband level changes are similar, suggesting that because the sideband level changes are similar, it proves that using the vibrations from operation is effective..

4.3 Conventional Vibro-Acoustic Modulation Tests

Conventional Vibro-Acoustic Modulation tests using two actuators were also performed on the same set of blades in order to validate the proposed technique. In these tests, the wind turbine blades were taken off the turbine and the roots of the blades were clamped onto a fixture to provide similar boundary conditions to the test conditions of on-turbine tests. To provide the pumping signal, a PCB disc actuator was installed. Due to its response characteristic, the actuator was operated at 400 Hz for the pumping signal excitation rather than using the pumping frequency used in the previous tests. The probing signal was provided by a MFC attached to the blades and the signal was measured by the MFC used in the previous tests. In order to determine the dependence of the Vibro-Acoustic Modulation results on the probing frequency, Vibro-Acoustic Modulation tests were also conducted with a signal swept between 5 kHz - 10 kHz as the probing signal. The responses at the probing frequencies and sideband levels over the different probing frequencies are plotted in Figure 7(c). Figure 7(c) also shows similar curves to those in Figure 7(a) and Figure 7(b).

These results indicate that the proposed technique, consisting of the Vibro-Acoustic Modulation test on the operating wind turbine blades and utilizing the structural vibration of the blades as the pumping signal, can measure the nonlinear characteristics of the blades as well as conventional types of pumping signals.

CHAPTER 5. COMPUTATIONAL STUDY

For a better understanding of the mechanism that causes a cracked blade to exhibit an increased nonlinear response during Vibro-Acoustic Modulation testing, the wind turbine blade used in this paper was modeled using finite elements. The blade was modeled as 32 Timoshenko beam elements, which include shear displacement as well as displacement due to the bending moment, connected in series along the span direction. To design this model, chord lengths and twisting angles were measure at 33 cross sections along the span of the blade. The airfoil shape was assumed as Wortmann FX63-137.

The crack was modeled by decreasing the cross-sectional area at the trailing edge of the airfoil only when crack opened. Therefore, the stiffness matrix for the simulation was recalculated with the reduced cross-sectional area and second moment area only when crack was open. The mass decrease due to the crack was not considered. In this simulation, a crack was propagated from the trailing edge at 0.3048 meters from the blade tip, which is the location of the crack in the experiments. The size of the crack was assumed as $r = l_{damaged} / c = 0.1$ where $l_{damaged}$ is the length of the crack and c is the chord length.

Figure 8 shows the calculated natural frequencies of the blade. The first calculated natural frequency was 9.09 Hz, a good match for the first natural frequency considering that it only differed from the experimentally determined natural frequency by 3 percent.

Setups for the simulated Vibro-Acoustic Modulation tests were modeled as follows. The force from the MFC actuator was modeled as a moment input because the force from the MFC is in-plane and expected to cause a bending moment rather a transverse force. The displacement, measured by the MFC sensor, was modeled as a transverse displacement because the MFCs measure strain on the surface that is proportional to the curvature. In theory, the curvature is not always proportional to the transverse displacement, but there is a strong relationship between the two so transverse displacement is assumed to be a reasonable indicator of the curvature.

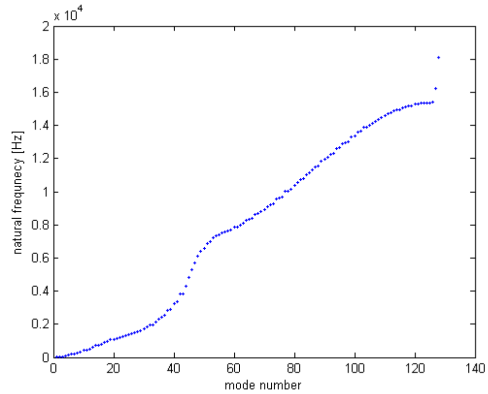

Figure 8. Calculated natural frequencies.

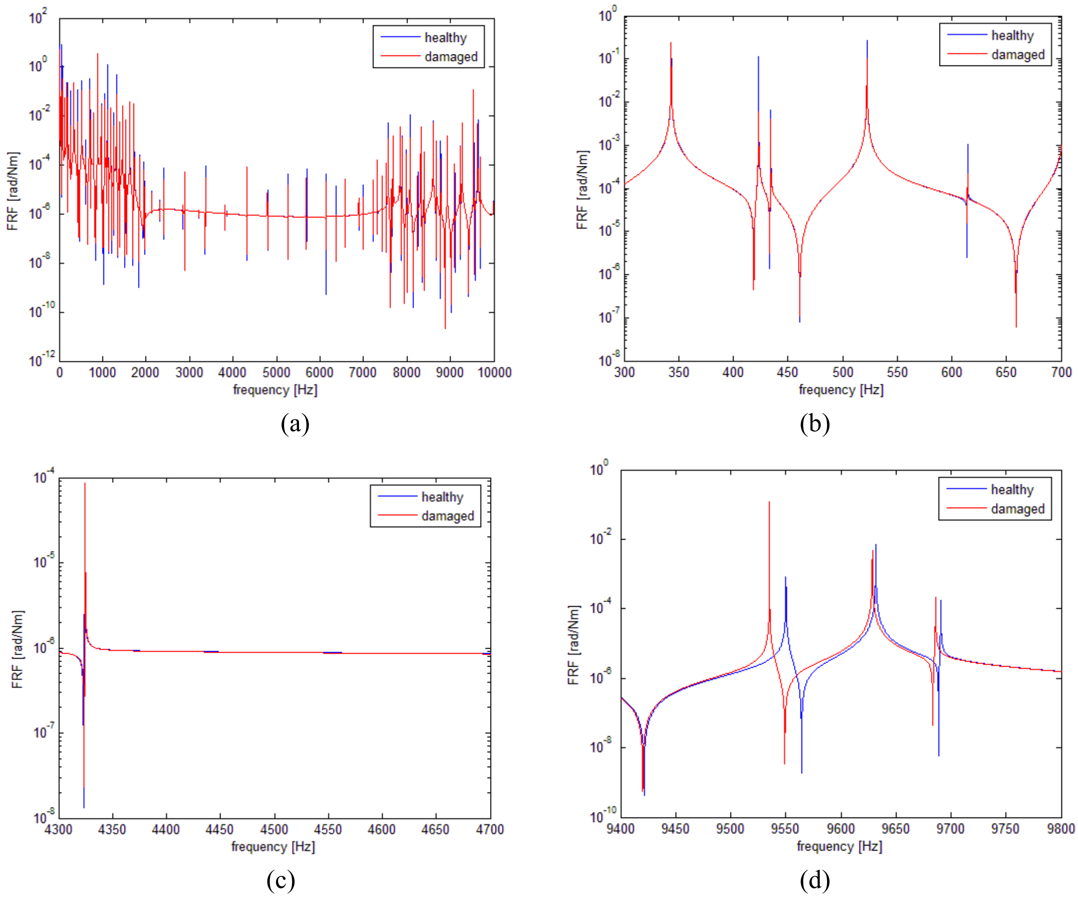

Figure 9. Frequency response function of the blade. (a) Overall range.
(b) Low-frequency range. (c) Mid-frequency range. (d) High-frequency range.

Figure 9 shows the frequency response function between the MFC actuator and MFC sensor of the healthy blade and damaged blade models. A frequency resolution $df = 0.1$ Hz was chosen because the minimum frequency difference between the natural frequencies was 2 Hz.

Figure 9(a) shows that the frequency response function in the range of f=2000~6000 Hz is relatively flat at most frequencies. This is partially attributed to fewer natural frequencies in this range as shown Figure 8. The sideband estimates from the model, based on the crack opening and closing motion theory, suggest that the modulation sidebands emerge due to a shift of the peaks in the frequency response function and changes in the frequency response function value at the pumping frequency [7].

Figure 9(b), the frequency response function in the low frequency range, has several peaks and has a highly frequency-dependent curve. However, it is difficult to find the difference between the curve of the healthy blade and that of the damaged blade. Therefore, the choice of probing frequency in this range would be an effective choice.

Figure 9(c), the frequency response function in low frequency range, has fewer peaks initially. Moreover, the curves throughout most of this range are flat. Therefore, it would be difficult to find modulation sidebands with the probing frequency in this range as well.

Figure 9(d) shows the frequency response function in an ideal frequency range for selecting a probing frequency. The frequency response functions are highly frequency-dependent and the difference between the curve of the healthy blade and that of the damaged blade is also large.

This result suggests that the probing frequency should be chosen carefully to effectively produce nonlinear modulation. This result also corresponds well with the experimental results. Figure 5(a)~Figure 5(c) show that there are larger differences in Vibro-Acoustic Modulation test results when the probing frequency was chosen at 9000~10000 Hz compared to when the probing frequency was chosen at 5000~6000 Hz.

CHAPTER 6. CONCLUSIONS

Wind turbines require a robust structural health monitoring strategy for wind turbine blades, and this research developed a new crack detection technique for wind turbine blades in operation using Vibro-Acoustic Modulation. The technique utilizes the structural vibration of the wind turbine blades as a pumping signal when the rotor rotates, and measures the sideband levels which are the result of the modulation between the probing signal generated from the piezoelectric actuator on the blade and the pumping signal.

When considering the application of this damage detection technique in the field with a utility-scale horizontal axis wind turbine, modifications may be necessary to account for the increased size of the structure and the varying rotational speed of the turbine due to the stochastic input provided by the wind resource. For example, the rotational speed of a utility-scale wind turbine will be much lower than that of the Whisper 100 turbine. Therefore, to detect modulation sidebands of the probing frequency, increased frequency resolution may be required. Another area of concern rises from the variable nature of the wind speed and environment outside of the laboratory. The blade rotational speed of the turbine will vary as the wind changes speed and direction. However, the modulation sidebands of the probing signal can be located as long as the location of the pumping frequency is known. Therefore, a measurement of the low frequency vibrational response of the blade would identify the location of the pumping frequency and resultant locations of the modulation sidebands. If such a measurement is not possible, then the rotor encoder signal could be used to determine the rotational speed of the turbine. Another common wind turbine environmental factor is lightning. The data acquisition system used to acquire the vibration data will be susceptible to lightning strikes like the other electronics and controls on the turbine, but this danger can be mitigated through the use of surge suppression and grounding with a lightning protection system. In addition, the MFC transducer is coated in a polyimide film and these materials are known to be good insulators.

This technique has many benefits for structural health monitoring of wind turbine blades. First, the technique does not require the wind turbines to be stopped in order to inspect the blades. Therefore, not only is the maintenance cost reduced, but there is also no loss of generated power from the turbines when they are taken offline for inspection. The technique is also beneficial because it is based on nonlinear property changes which are sensitive to small defects. Therefore, the technique can detect small cracks in blades earlier than other techniques normally would. Furthermore, the technique is less affected by various environmental and loading conditions such as temperatures, humidity, wind profile, etc. than the presence of the cracks in the blades. Finally, the technique can be performed with cost-effective excitation system because the nonlinear characteristics of the excitation system do not affect sidebands levels which present nonlinear characteristics of the material.

In this paper, the Vibro Acoustic Modulation technique on an operating wind turbine blade was demonstrated with a Whisper 100, 900 Watt small-scale wind turbine. The test results showed that the proposed technique can measure the nonlinearity in the response of the blades using the structural vibration as the pumping signal in operation as effectively as using other conventional Vibro-Acoustic methods that are implemented using different types of pumping signals. In addition, a computational frequency response function comparison between a healthy blade and a damaged blade showed that it is important to choose a proper probing frequency in order to maximize the sensitivity of the proposed technique to cracks.

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