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Measurements of UWB Pulse Propagation Along a Wind Turbine Blade at 1 to 20 GHz

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Abstract—**This paper describes propagation measurements of an Ultra Wide Band (UWB) pulse along a full-scale wind turbine blade. The aim is to use the UWB channel characteristics to determine the deflection of the wind turbine blade under different wind loads. The frequency response is measured from 1 to 20 GHz and by use of Fast Fourier Transform (FFT) studied the delay domain. It has been found challenging to determine the deflection of the blade only by looking at the delay difference between the Line-Of-Sight (LOS) pulse and a pulse reflected from the blade. To determine from which area of the blade the reflection originates a ray-tracing study incorporating a model of the curvature of the blade have been conducted. This showed the area causing the reflections depended highly on the placement of the antenna on the wind turbine blade.**

Index Terms—**Wind turbine blade, UWB channel, UWB pulse, UWB ranging, Time of Arrival**

I. INTRODUCTION

Wind turbines are widely used all over the world to produce renewable energy. Modern wind turbines are utilizing long turbine blade's to improve their efficiency. These long blades are easily deflected when subjugated to strong winds. Under very strong winds the blades deflection can be so pronounced that there is a risk of striking the turbine tower as described in [1]. However, this problem can be addressed by applying a pitch to the blades which ensures a safe distance to the turbine tower. Pitching the blades will decrease the efficiency of the wind turbine. Therefore, to optimize the efficiency, it is of interest to know the precise deflection of the wind turbine blades.

One method is to determine the deflection of the wind turbine blade using Ultra Wide Band (UWB) ranging as described in [2]. The idea is to place antennas near the tip and the root of the wind turbine blade and by using the time of arrival (ToA) of the UWB pulse determine the distance between the transmit (Tx) and receive (Rx) antenna. The distance between antennas can then by applying trigonometry be used to determine the deflection of the wind turbine blade. The development of this technique is the main goal for the iRoter project. In [3] this new application of utilizing UWB technology for wind turbine blade deflection sensing has been introduced. In [4] a tip antenna, described in [5], has been placed inside the blade and systems performance has been verified by simulations and full-scale measurements. Further results have been published in [6].

In those papers, the system is implemented in the frequency band of 3.1 GHz to 5.3 GHz. In this paper, the wideband propagation channel along the wind turbine blade will be studied in the frequency range 1 GHz to 20 GHz. Measurements have been conducted in the frequency domain and the possibility of estimating the blade deflection by investigation of the impulse response is described. The impulse response for both the full 1 GHz to 20 GHz bandwidth together with four sub-bands, 1 GHz to 5 GHz, 5 GHz to 10 GHz, 10 GHz to 15 GHz and 15 GHz to 20 GHz have been investigated. To determine from which area the signal is reflected on the wind turbine blade a ray-tracing study has been conducted. This includes a model for how the surface slope changes on the surface of the blade depending on the level of deflection.

The paper is organized as follows. Section II describes a ray-tracing study of the wind turbine blade. Section III describes the measurement setup. Section IV presents the resulting impulse response of the full bandwidth while Section V presents the results of the for sub-bands. Section VI summarizes this work.

II. RAY-TRACING STUDY

The wind turbine blade is suspended in the air when the UWB ranging system is to be deployed. This means that the only source of reflections near to the UWB ranging system is the blade itself. A simplification of the expected propagation environment can due to this be expressed as the two-ray model, seen in Fig. 1.
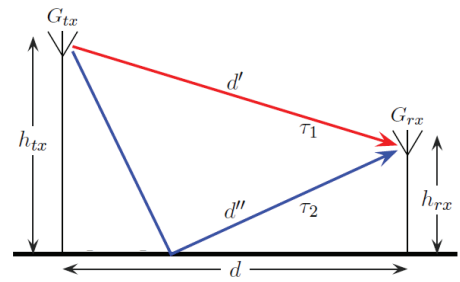
Fig. 1: Simplification with the 2 Ray model.

In Fig. 1 the distance of the LOS signal is denoted d' (Red). The reflected signal is denoted d'' (Blue). The time of flight for the two paths/rays is denoted τ_1 and τ_2. The true distance between the antennas is denoted d. The heights of the antenna above the reflecting surface (wind turbine blade) are denoted respectively with h_{tx} and h_{rx}. The antenna gains are denoted by G_{tx} and G_{rx}.

The two distances, d' and d'' can be found based on the geometry as shown in Eq. 1.

$$d' = \sqrt{d2 + (h_{tx} - h_{rx})^2}$$
$$d'' = \sqrt{d2 + (h_{tx} + h_{rx})^2}$$
(1)

A difference between the distances presented in Eq. 1 results in signal components arriving at different times as the propagation time for each signal component (ray), denoted by τ, is found as $\tau = d/s$. Where d is the distance traveled and s is the propagation speed. To be able to separate the LOS and reflected ray it is clear that the arrival time has to be significantly different. This difference is determined by the elevation of the antennas which clearly indicates that the placement of the antennas is important to investigate in the development of a UWB ranging system.

As the wind turbine blade is deflecting the simple two-ray model, where the reflecting surface is assumed flat, starts to fail. This is due to the added curvature of the surface of the wind turbine blade causing the reflections. To study this a model of the change in the shape of the wing when deflected have been developed. By applying simple ray-tracing it is possible to identify the areas of the blade surface causing reflections.

In the simulations two different positions where used for the root antenna (Rx), one perpendicular to the upwind side (uw) and one on the downwind side (dw) of the wind turbine blade. At both positions, the antenna was elevated on a mast by 40 cm. The tip antenna (Tx) was mounted on the surface of the blade. The simulations have been done for three different levels of deflections, no deflection, half deflection and full deflection. The resulting simulation is seen in Fig. 2.

In Fig. 2 it can be seen that the area causing the reflections is different depending on the placement of the root antenna. I general the downwind placement of the antenna causes reflections close to the tip of the blade while the upwind placement causes reflections close to the root of the blade. This information is interesting for a further development of a UWB ranging system for the wind turbine blades.

III. MEASUREMENT SETUP

To further study the feasibilies of a UWB ranging system measurements have been conducted in the frequency range 1 GHz to 20 GHz. The measurement has been conducted while the wind turbine blade is suspended in the air over RF absorber. This is done in order to mimic the conditions described for the simulations where only the wind turbine blade will cause reflections. The used measurement can be seen in Fig. 3.

In the measurement, there are two different positions of the root antenna (Rx), one perpendicular to the leading edge of the wind turbine blade as shown in Fig. 3a and one on the downwind side of the blade as shown in Fig. 3b. At both positions, the antenna was elevated on a mast by 40 cm. The tip antenna (Tx) was mounted on the surface of the blade.
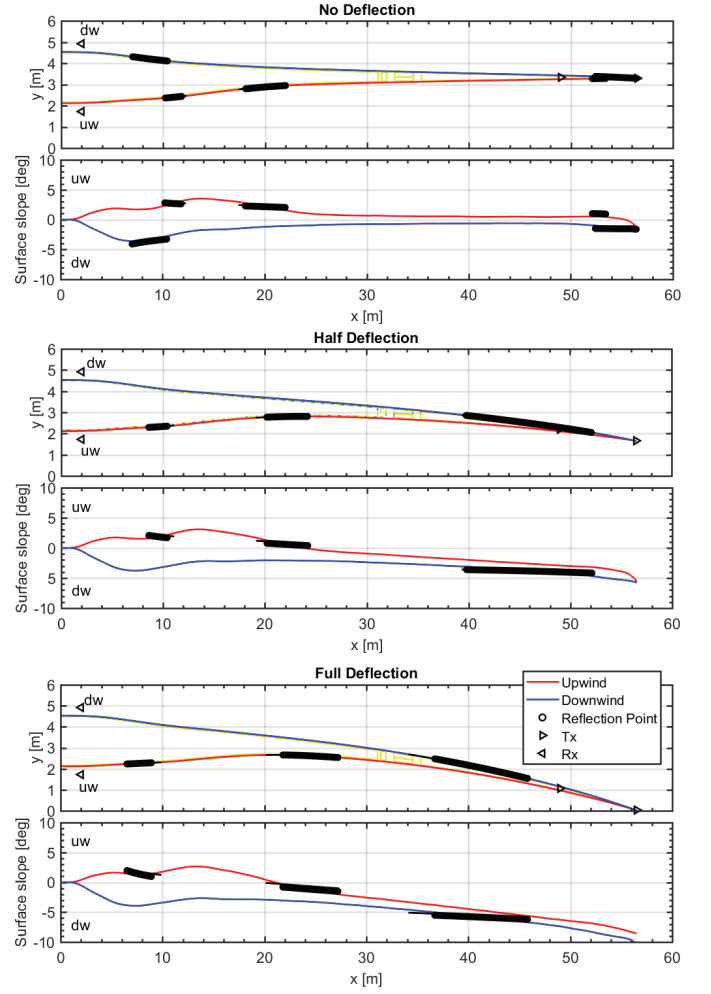

Fig. 2: Ray-tracing conducted for different levels of blade deflection. The reflection areas on the blade is shown for each deflection level together with the blade curvature (surface slope) at the reflection area.

In Fig. 3 d_{LOS} denotes the distance of the LOS ray and d_{ref} denotes the distance of the reflected ray from the tip to the root antenna. The difference between a deflected blade and a blade with no deflection is indicated with respectively red and black color.

The length of the measured wind turbine blade is 30 m. Thus, the expected path difference between the reflected and LOS rays for the blade with no deflection is 0.0107 m, which corresponds to the difference in the delay of 35.607 ps.

The measurements have, like the simulations, been done for three different levels of deflections, no deflection, half deflection and full deflection. For each of these deflection levels, the frequency response has been recorded between the antennas using a Vector Network Analyser (VNA). The measurements have been done in four bands: 1 GHz to 5 GHz, 5 GHz to 10 GHz, 10 GHz to 15 GHz and 15 GHz to 20 GHz as it was more convenient and to enable compensation of the frequency dependent antenna gains. The antennas have been
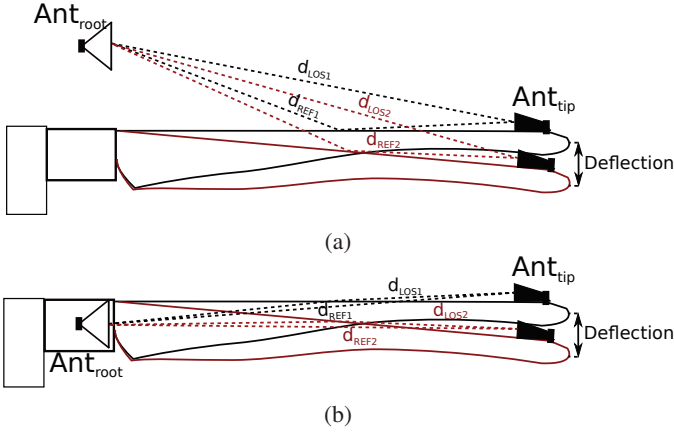
Fig. 3: Measurement setup of the wind turbine blade with: (a) edge mounted root antenna and (b) side mounted root antenna.

compensated by using a priori knowledge of the antenna gain for each of the frequencies. The phase response of the antennas have not been available and thus was not compensated for.

IV. FULL FREQUENCY BAND

The reason for wanting to investigate the full frequency band is in the definition of the absolute resolution of the commonly used for time of arrival (ToA) techniques. Using the assumption that the speed the signal propagates with is constant at the speed of light. The accuracy of these technique is dependent on the bandwidth of the signal as shown in Eq. 2 [7].

$$res_{abs} = \frac{c}{BW} \qquad (2)$$

where res_{abs} is the absolute resolution, c is the propagation speed approximated by the speed of light and BW is the bandwidth of the signal.

To investigate the full frequency band from $1\,\text{GHz}$ to $20\,\text{GHz}$ the four measured band have been combined. The total channel transfer function is therefore created from all four measured bands and mirrored to create a negative side of the spectrum. To complete the full channel transfer function zeros has been added below the frequency of $1\,\text{GHz}$. Furthermore, the Hamming window function has been used over the frequency response.

The resulting frequency response is shown in Fig. 6(a) for the root antenna located on edge and in Fig. 6(b) for the root antenna located on the side of the blade. It can clearly be seen that the transfer function curves for the full deflection have less frequency selective fading than the curves for the half and no deflection. The overall shape of the frequency response is different for the measurements with the root antenna on the edge and side. Especially, can a difference be observed for the curve for the full deflection. The magnitude of the transfer function from 1 to 5 GHz is much higher for the root antenna mounted on the side of the blade.

The impulse response of the channel, obtained by FFT, is shown in Fig. 6(a) for the root antenna on the edge and in Fig.
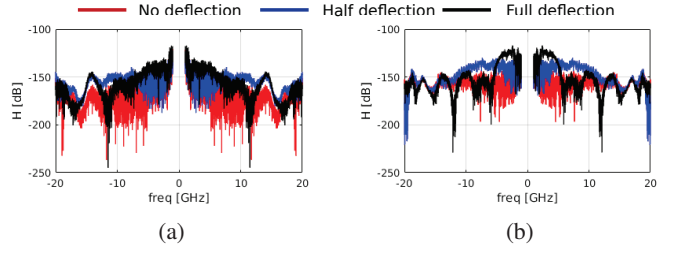

Fig. 4: Frequency response of: (a) edge mounted root antenna and (b) side mounted root antenna.

6(b) for the root antenna on the side. It can clearly be seen that a maximum amplitude of the LOS pulse is higher for the root antenna mounted on the side of the blade. The reflection from the room, in which the measurements took place, occurs at $\tau = 113\,\text{ns}$, thus the impulse response data after 113 ns is not relevant and is not shown in the figures.
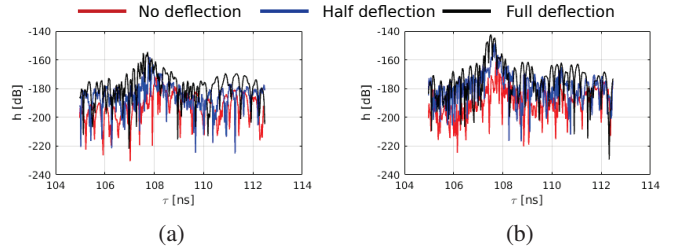

Fig. 5: Impulse response of: (a) edge mounted root antenna and (b) side mounted root antenna.

Fig. 6 shows a zoomed version of the arrival time close to the LOS pulse for both the edge and side mounted root antenna. It can be noticed that first pulse (LOS) and reflected pulse from the blade only can be distinguished at full deflection of the blade. Otherwise, it is challenging to see the reflected pulse. The delay difference between first and second pulse is between $150\,\text{ns}$ and $160\,\text{ns}$, which is roughly 4 times larger than the delay difference calculated for the straight blade.
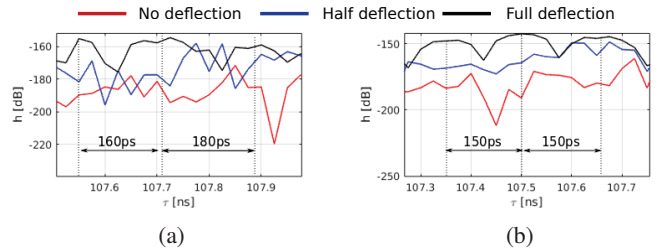

Fig. 6: Zoomed in impulse response of: (a) edge mounted root antenna and (b) side mounted root antenna.

From this study it is clear that using the full frequency band from $1\,\text{GHz}$ to $20\,\text{GHz}$ might not be a usable solution

for UWB ranging. Due to this, a study of the four sub-bands has been presented in the following.

V. COMPARISON BETWEEN FOUR FREQUENCY BANDS

The comparison of the four different frequency bands is shown in Fig. 7 for the edge mounted and in Fig. 8 for the side mounted root antenna. The first impression from these plots when compared to Fig. 5 is that the time resolution is lower, this is related to Eq. 2. For all the four bands it is impossible to distinguish the reflected pulse and the LOS pulse. This is because the lowered resolution now results in a pulse width larger than the delay difference between reflected pulse and LOS pulse.
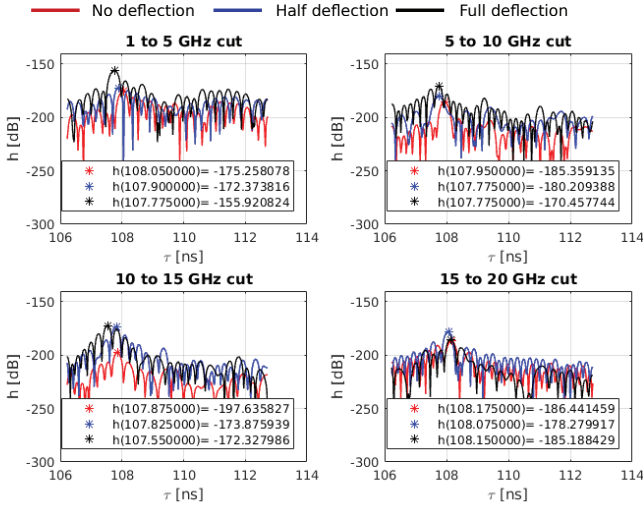

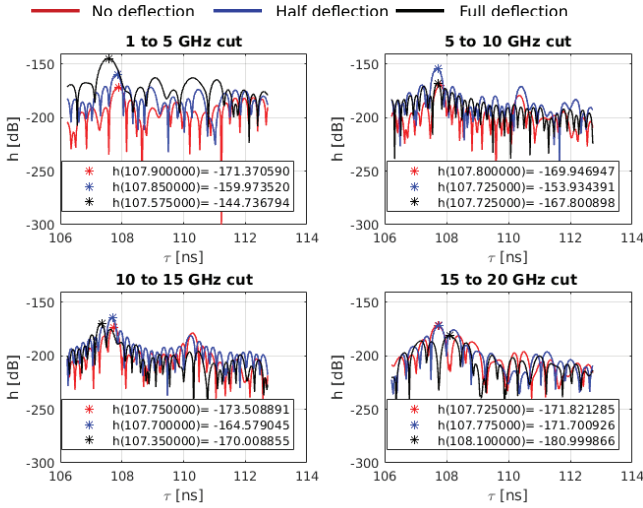Fig. 7: Edge mounted antenna.

Fig. 8: Side mounted antenna.

From Fig. 7 and Fig. 8 it can be seen that the maximum amplitude of the impulse response (LOS pulse) differ from one band to the other. The amplitude at $1\,\mathrm{GHz}$ to $5\,\mathrm{GHz}$ have similar characteristics as found for the full band shown in Fig. 5. The impulse response for the maximum deflection have the highest amplitude while the impulse response for the medium and no deflection have respectively medium and low amplitude. In $5\,\mathrm{GHz}$ to $10\,\mathrm{GHz}$ band the amplitude for the edge antenna have similar characteristics, but impulse response for the medium deflection have the highest amplitude in case of the root antenna mounted on the side of the blade. In the $10\,\mathrm{GHz}$ to $15\,\mathrm{GHz}$ band in the edge mounted antenna case the amplitude of the LOS pulse for the straight blade is $24\,\mathrm{dB}$ lower then the amplitude the LOS pulses for the deflected blade. In $15\,\mathrm{GHz}$ to $20\,\mathrm{GHz}$ band all of the LOS pulses are closer to the noise floor in respect to the other three bands. The amplitude of the LOS pulses are very similar and varies between $7\,\mathrm{dB}$ and $9\,\mathrm{dB}$.

The delay difference between the LOS and reflected UWB pulse at the four different frequency bands is shown in TABLE I.

TABLE I. Delay difference $\Delta\tau$ of the LOS pulse in 4 frequency bands.

Deflection	1-5 GHz	5-10 GHz	10-15 GHz	15-20 GHz
None	150 ps	150 ps	125 ps	450 ps
Half	50 ps	50 ps	125 ps	300 ps
Full	200 ps	50 ps	200 ps	50 ps

VI. CONCLUSION

In this paper, the Ultra Wide Band (UWB) pulse propagation characteristics of the channel along the wind turbine blade have been investigated.

A simulation model capable of indicating the areas on the wind turbine blade causing reflections have been developed and used on a model of the wind turbine blade. It is found that the placement of the antennas on the blade, as expected, highly determines the reflection area.

Measurements have been conducted along the wind turbine blade in the frequency range from $1\,\mathrm{GHz}$ to $20\,\mathrm{GHz}$. The resulting impulse response for the full $1\,\mathrm{GHz}$ to $20\,\mathrm{GHz}$ bandwidth together with four sub-bands, $1\,\mathrm{GHz}$ to $5\,\mathrm{GHz}$, $5\,\mathrm{GHz}$ to $10\,\mathrm{GHz}$, $10\,\mathrm{GHz}$ to $15\,\mathrm{GHz}$ and $15\,\mathrm{GHz}$ to $20\,\mathrm{GHz}$. It has been found that it is challenging to estimate the blade deflection by reading the delay difference between Line-Of-Sight (LOS) pulse and a pulse reflected from the wind turbine blade even if the frequency range from $1\,\mathrm{GHz}$ to $20\,\mathrm{GHz}$ has been used. The $15\,\mathrm{GHz}$ to $20\,\mathrm{GHz}$ band has shown minimum variations in LOS pulse amplitude. But LOS pulses at the lower bands have higher overall magnitude because of the lower path loss. The deflection can be estimated by looking at the difference in the delay between LOS pulses received from two different root antennas. The $1\,\mathrm{GHz}$ to $5\,\mathrm{GHz}$ and $10\,\mathrm{GHz}$ to $15\,\mathrm{GHz}$ bands have shown the highest delay difference at the full deflection of the blade. In the $15\,\mathrm{GHz}$ to $20\,\mathrm{GHz}$ the delay difference for the low and no deflection shown the highest numbers.

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