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Published in:
IEEE Access

DOI (link to publication from Publisher):
10.1109/ACCESS.2018.2819880

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received February 20, 2018, accepted March 19, 2018, date of publication March 29, 2018, date of current version April 25, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2819880

Antenna Gain Impact on UWB Wind Turbine Blade Deflection Sensing

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This work was supported by the InnovationsFonden Project of Intelligent Rotor for Wind Energy Cost Reduction.

ABSTRACT Antenna gain impact on ultra-wideband wind turbine blade deflection sensing is studied in this paper. Simulations are applied with a 4.5-m blade tip. The antennas with high gain (HG) and low gain (LG) in free space are simulated inside a blade. It is interesting to find that tip antennas with HG and LG in free space have similar realized gain when allocated inside blades, so that the emission power for the HG and LG antennas in blades can be the same. The antenna gain impacts on time-domain pulse waveforms and power distributions around a blade are carefully investigated (with the tip antenna inside a blade). Higher antenna gain enlarges both direct pulse and multipath but in different levels. To verify the simulations, time-domain measurements are performed with a full 37-m blade. Pulse waveforms and power delay profiles are measured. From all the studies, it follows that, with the similar effective (or equivalent) isotropic radiated power, an HG tip antenna inside a blade gives stronger direct pulse amplitudes and better pulse waveforms for accurate and reliable distance estimations than the LG. Moreover, the direct pulse with the HG antenna is also closer to the blade surface, which is important for the deflection sensing of a blade over 37 m.

INDEX TERMS Antenna gain, radiation pattern, UWB, sensor, wind turbine, blade deflection.

I. INTRODUCTION

Wind power has attracted great attention as a type of clean and sustainable energy, which can be harvested by wind turbines. It is highly preferred if wind turbine blades can be made longer without increasing its weight. In this way, we can capture and transform more wind energy into power without additional cost. However, a longer and lighter blade is less stiff and easier to bend towards the tower when wind loads on it, as illustrated in Fig. 1. It increases the risk of the over-deflected (or over-bent) blade striking the tower (tower strike). In order to avoid the tower strike, a sensing system is required to monitor the deflection of a blade, so that a control can be applied in advance before a predicted tower strike.

The sensing systems have to be robust enough to survive in harsh operating environments of wind turbines for over 20 years. The blade tip of a wind turbine typically travels at the speed of over 250 km/h and vibrates with the acceleration of over 100 m/s^2. The sensing system should not change the blade surface curvature. Lightning protection of the sensing systems is also an important issue. Some techniques have been developed during the past few years, such as strain gauge sensors [1], optical fiber sensors [2], micro-electro-mechanical system (MEMS) sensors [3], local aerodynamic sensors [4], laser sensors [5], and so on. However, since these techniques are difficult to monitor the deflection reliably for over 20 years or longer, they have not been widely implemented in industry.

Ultra-wideband (UWB) technology has been utilized in many applications such as communications [6], localizations [7], energy harvesting [8], and so on. A UWB wind turbine blade deflection sensing system is first introduced in [9] with a tip antenna mounted on the external blade surface. A low-profile UWB antenna is also proposed for this system in [10]. As illustrated in Fig. 1, each blade implements one UWB deflection sensing system. The sensing system is composed of one transmitting antenna at the blade tip and two receiving antennas at the blade root. A UWB pulse is transmitted from the tip antenna to the two root antennas. By calculating the flying time of the direct UWB pulse, two tip-root antenna distances can be estimated. The blade deflection is calculated by the triangulation of two estimated tip-root distances. The tip antenna has to be placed inside the

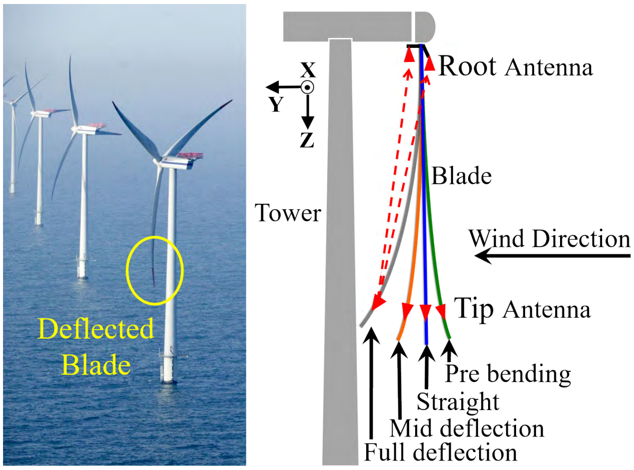


FIGURE 1. Sketch of a UWB wind turbine blade deflection sensing system.

blade [11], as its placement outside would produce excessive aerodynamic noise and make lightning protection difficult. The optimal antenna polarization and two root antenna locations have been found in [11]. However, a blade is a hollow dielectric tube made of a lot of lossy materials. Multipath with an in-blade tip antenna is much stronger than that with an external tip antenna. The multipath will severely weaken and interfere the direct pulse for distance estimations. This increases the risk of the system locking on the wrong pulse and resulting in the fault of deflection tracking. In [12], it is found that the multipath is mainly contributed by the leaky wave radiated from the surface waves propagating along the external blade-shell surface. An absorber has been placed inside a blade to significantly attenuate the surface waves and suppress the multipath [12].

As a transmitter, the gain of an in-blade tip antenna may affect the received pulse waveform. On one hand, the tip antenna with high gain enlarges the amplitude of the direct pulse. On the other hand, the high gain of the tip antenna will also strengthen the surface waves on the external blade surface and lead to severe multipath interference. It is very important to study how the tip antenna gain impacts the received pulse waveform and the distance estimations between the tip and root antennas. Furthermore, the gain of a tip antenna inside a blade also limits the maximum system transmitting power influencing pulse waveform amplitudes.

In this paper, we will focus on the investigation of antenna gain impact on UWB wind turbine blade deflection sensing. The UWB band of 3.1-5 GHz will be used. Simulations will be performed with a 4.5-meter blade tip section. The transmitting power of a sensing system is directly related to the gain of a tip antenna inside a blade due to the limitation of effective (or equivalent) isotropic radiated power (EIRP). The realized gain with the tip antenna inside the straight or deflected blade will be simulated in the frequency domain. Simulations are performed to study the antenna gain impact on pulse waveforms and power distributions. To verify the tendencies in the simulations, full-blade time-domain measurements will

TABLE 1. Realized gain of antennas inside straight and deflected blades in frequency domain.

	Free space	Straight blade	Mid deflected blade	Full deflected blade
LG antenna (Average/ Peak) (dBi)	11/11.6	13.6/15.2	14.7/17	15.5/**17.1**
HG antenna (Average/ Peak) (dBi)	15.2/15.4	14.4/**17.6**	15.5/17.5	15/16.8

be carried out with a 37-meter blade. Pulse waveforms will be measured above both the downwind surface and the leading edge with a time-domain UWB pulse generator. Pulse power delay profiles will be measured above downwind surface with a 2-meter scan arm.

II. SIMULATIONS WITH A SMALL PART OF BLADE TIP

In this section, we will simulate and study the antenna gain impact on a straight and deflected blade with one small part of the blade. Later the tendencies obtained from simulations will be verified by full-blade time-domain measurements. In this paper, all the simulations are carried out with the CST Microwave Studio 2017.

A. SIMULATION SETUPS

The simulation setups are shown in Fig. 2. The UWB band of 3.1-5 GHz is applied for this application. Fig. 2 (a) illustrates the geometries of a full blade, the tip section of the blade used for the simulations, and the location of a tip antenna inside the blade. A conventional wind turbine blade is a long (over 37 meters) and hollow tube made of the fiberglass with the permittivity of 4.4 and loss tangent of 0.03. The thickness of the blade shell varies from around 5 mm at the blade tip to several centimeters at the blade root. In the simulations, only a 4.5-meter blade tip section is utilized due to the limitation of the memory in a regular desktop computer. A tip antenna is placed inside the blade. In the investigations, we will use the antennas with high gain (HG) and low gain (LG). In order to minimize the impact of different antenna configurations on the results, the HG and LG antennas have been kept as similar as possible, as shown in Fig. 2 (b). The average and peak realized gain of the HG and LG antennas in free space is provided in Table 1. Fig. 2 (c) shows the straight and deflected blade tip sections utilized in the simulations. The blade tips with mid deflection and full defection are bent by 15degree and 30degree, respectively. Please note that: in the full deflection, the blade tip will be bent by 30degree, but the angle between the tip-root antenna link and the (full) blade root surface is less than 15degree.

B. VALUES OF ANTENNA GAIN INSIDE STRAIGHT AND DEFLECTED BLADES IN FREQUENCY DOMAIN FOR EIRP

The EIRP of a UWB system is constrained by FCC standards, and the maximum EIRP within the UWB band of 3.1-5 GHz

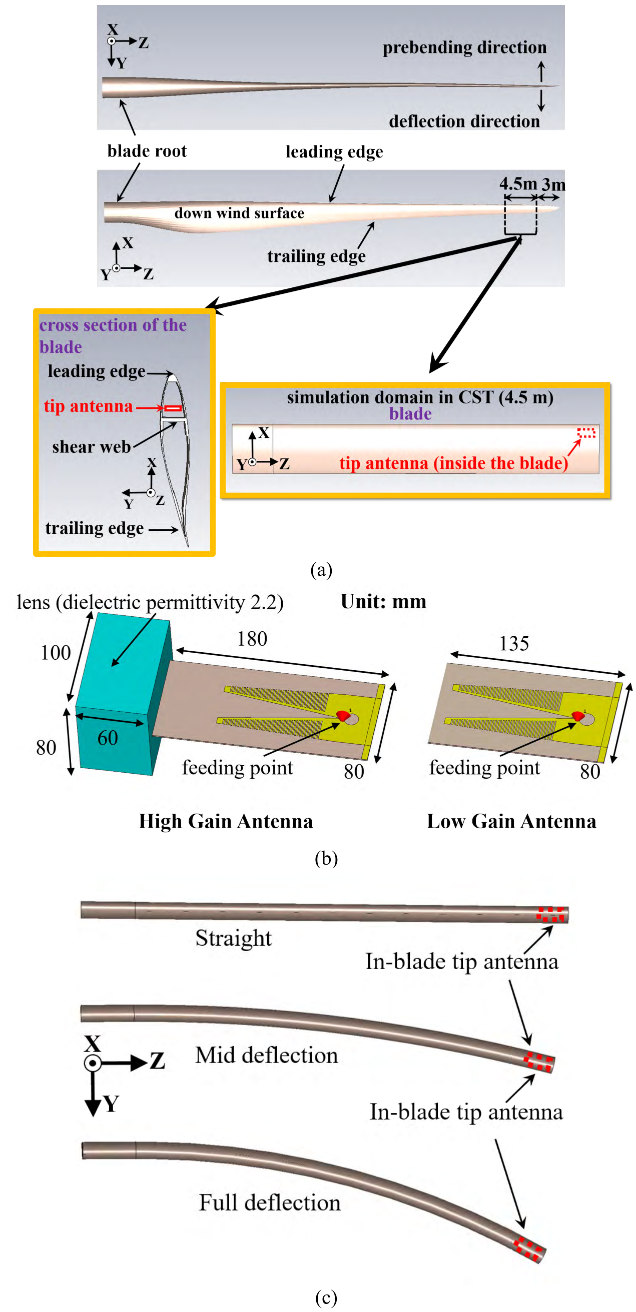


FIGURE 2. Simulation setups: (a) a straight blade with a tip antenna inside, (b) tip antennas with high gain and low gain, and (c) straight and deflected blade tip sections used for simulations.

is −41.3 dBm/MHz [13]. EIRP is defined as:

$$EIRP = P_{in} - L + G_{antenna} \quad (1)$$

where P_{in} is the maximum input transmitting power of the whole system, L is the cable loss, and $G_{antenna}$ is the realized gain of an antenna. The antenna gain will directly affect the maximum transmitting power due to the EIRP limitations. The average and peak realized gain of the tip antennas inside the straight and deflected blades is given in Table 1. In free space, there is around 4 dBi difference between the HG and LG antennas. However, when the antennas are placed inside blades, the average gain of two antennas is similar in straight and deflected blades. The maximum transmitting power of two antennas should also be similar if the EIRP is calculated by the average gain of two antennas over the band of 3.1-5 GHz. Furthermore, the maximum gain of the HG and LG antennas is 17.6 dBi and 17.1 dBi within the UWB band and under different deflections, respectively. If the EIRP is evaluated by the maximum gain, the maximum emission power of two antennas should also be very close. Therefore, even though we use the antennas with different gain in free space, the average and peak gain of the HG and LG antennas inside blades are similar. In the following studies, we will apply the same input transmitting power for the simulations with the HG and LG antennas in a blade.

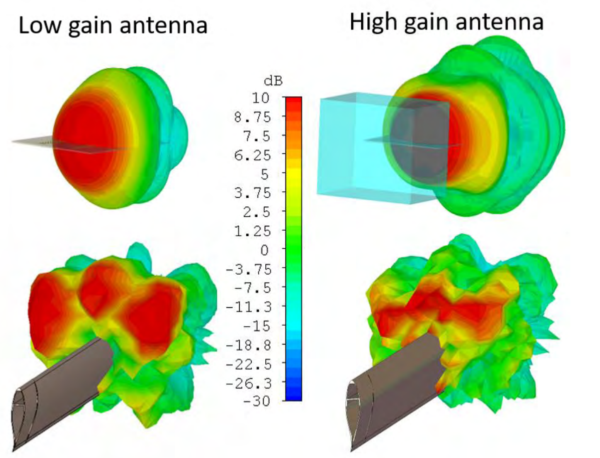


FIGURE 3. Simulated radiation patterns of antennas with high gain and low gain in free space and in a straight blade section at 4 GHz.

Fig. 3 shows the simulated radiation patterns of antennas with HG and LG in free space and in a straight blade tip section at 4 GHz. It is observed that blades modify the radiation patterns of the antenna in free space due to antenna-blade interactions. It can explain why the antennas with different gain in free space will have similar gain when allocated inside blades. However, it is also noticed that the in-blade tip antenna with higher gain will make the radiated power distributed closer to the blade surface (see Fig. 3).

C. ANTENNA GAIN IMPACT ON A STRAIGHT BLADE

Antenna gain impact on the time-domain pulse waveform and pulse power distribution around a straight blade will be studied in the following.

To analyze the time-domain pulse waveforms, electric-field probes are added above the downwind surface and the leading edge of the blade tip section, as shown in Fig. 4 (a). The probes are 3.9 meters away from the tip antenna. Two probes are the 15 cm off the blade downwind surface and 15 cm off the blade leading edge, respectively. The input pulse with the frequency bandwidth of 3.1-5 GHz is shown in Fig. 4 (b). Fig. 4 (c) presents the output pulse waveforms

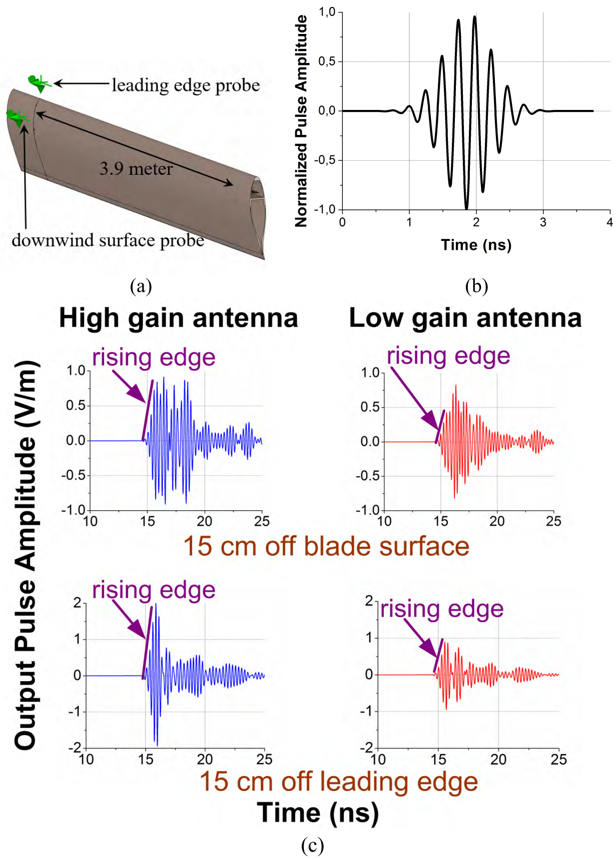


FIGURE 4. Simulated time-domain pulse waveform: (a) E-field probes, (b) the input pulse, and (c) the output pulses.

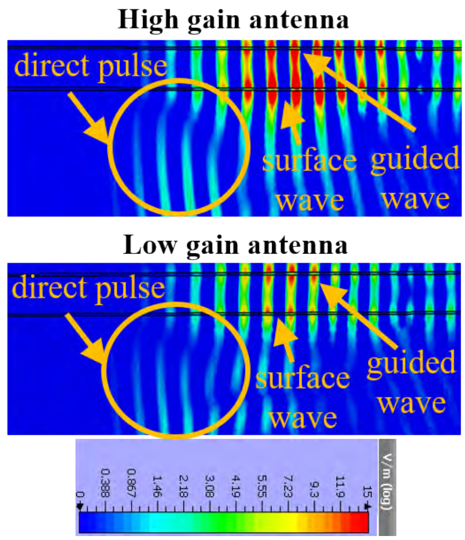


FIGURE 5. Simulated pulse power distribution above the downwind surface of a straight blade section at 13 ns in space.

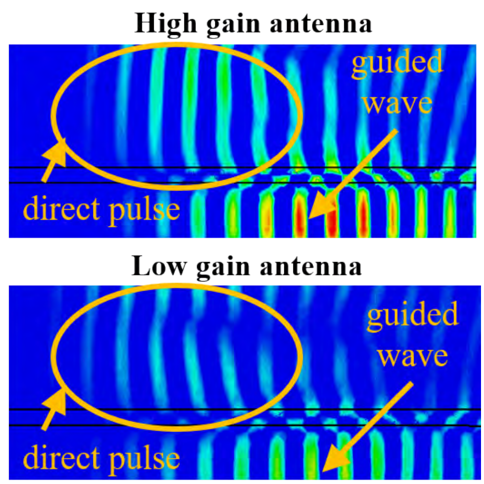


FIGURE 6. Simulated pulse power distribution above leading edge of a straight blade section at 13 ns in space.

of the probes. It can be observed that the rising edges of pulse waveforms with the HG antenna are always stronger than those with the LG antenna. Indeed, the HG antenna gain amplifies both direct pulse and multipath pulse but in different levels. With the HG antenna, the direct pulse are enlarged more than the multipath, so that the direction pulse is more distinguished out of the multipath. Therefore, the antenna with HG should be applied in order to have a strong direct pulse and a good pulse waveform, which indicates accurate and reliable distance estimations. In [12], an absorber has been applied to suppress multipath. It can also be considered as a method of making the direction pulse more distinguished out of the multipath. The main purposes of ultilizing absorber and HG antenna are similar. In addition, please note that in all the investigations of this paper, multipath effects are always included.

In order to better understand how the antenna gain impacts the quality of time-domain pulses, Fig. 5 and Fig. 6 show the simulated pulse power distributions above the downwind surface and leading edge of a straight blade tip section at 13 ns in space, respectively. The color bar in Fig. 6 is the same as that in Fig. 5. The power of the direct pulse with the HG antenna is stronger and closer to the blade surface and the leading edge than that with the LG antenna. It is very important to have the strong direct pulse close to blade surface in the applications. This is because, due to the extremely long blade, root antennas can only receive the pulses from a very small angle along the blade surface (less than 15 degree), especially in the case of a straight blade. Since a blade is made of lossy materials, the direct pulse close to blade surface is attenuated and weaker than that far away from the surface. Weak direct pulses may decrease the accuracy and reliability of the distance estimations and deflection sensing. In addition, it can also be noticed that the power of the surface and guided waves in the case with HG antenna are also enhanced, but the direct pulse rising edge is not interfered by these waves.

D. ANTENNA GAIN IMPACT ON A DEFLECTED BLADE

In the following, we will investigate the antenna gain impact on a deflected blade. The simulated pulse power distribution above the downwind surface of a blade tip section with mid

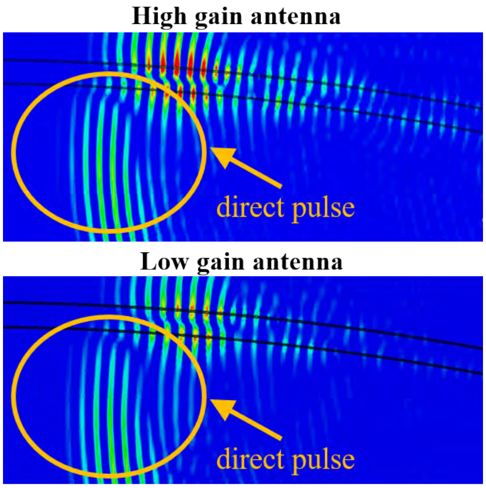


FIGURE 7. Simulated pulse power distribution above the downwind surface of a blade tip section with mid deflection at 13 ns in space.

deflection is provided in Fig. 7, where the color bar is the same to that in Fig. 5. Compared with the straight blade case, both the HG and LG antennas in a blade have stronger pulse power with mid deflection. As aforementioned, the pulse power further away from the blade surface is stronger than that close to the blade surface. When a blade is deflected, the blade surface curvature close to the tip antenna is nearly the same. The pulse power distribution in a deflected blade is similar to the distribution in a straight blade which is rotated (to the strong pulse direction) by a certain degree. It can also be found that the direct pulse power with the HG antenna is still slightly stronger compared to the LG (but not as much as that in the case of a straight blade). In a fully deflected blade, the conclusions are similar, where the details will not be explained here again.

III. FULL-BLADE TIME-DOMAIN MEASUREMENTS

In the simulations, we have found the tendencies that tip antennas with high gain give better direct pulse quality in straight and deflected blades. Since only a blade tip section is utilized in the simulations, in this section full-blade time-domain measurements will be carried out to verify the tendencies. The case in a straight blade is the most challenging scenario based on the studies above and in [12]. Moreover, the direct pulse quality will significantly be improved in a deflected blade. Therefore, the measurements will mainly focus on the straight blade case.

In addition, the 3D radiation patterns of the tip antenna inside a blade or the pulse power distributions in a deflected blade are not measured in the paper. A blade length is over 37 meter and very heavy. Even including a small part of a blade (e.g. 4.5 meters), it is still difficult to find a chamber to measure the 3D radiation patterns of an in-blade tip antenna. Moreover, all the deflected blades have to be measured in a test center (as shown in [9]). However, it is not allowed to stay inside the center to measure radiation patterns or pulse power distributions when a blade is deflected due to the safety reason.

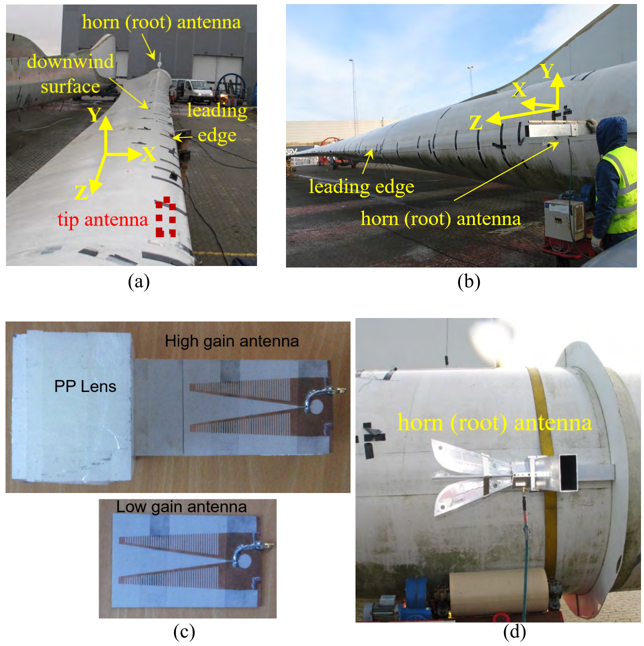


FIGURE 8. The setups of full-blade time-domain pulse waveform measurements: (a) pulse waveform measurement above downwind surface, (b) pulse waveform measurement above leading edge, (c) tip antennas with high gain and low gain, and (d) the horn antenna at the blade root.

A. SETUPS AND RESULTS OF FULL-BLADE TIME-DOMAIN PULSE WAVEFORM MEASUREMENTS

The setups of full-blade time-domain pulse waveform measurements are illustrated in Fig. 8. A 37-meter blade produced at LM Wind Power [14] has been used in the measurements. The pulse is transmitted from a tip antenna allocated inside the blade and received by a root antenna in the downwind surface directions, as shown in Fig. 8 (a). Fig. 8 (b) presents the waveform measurement setups in the leading edge directions. The pulse waveforms are recorded with the root antenna at different heights above the downwind surface and leading edge. In practical applications, the distance between the root antenna and the blade root surface should be as small as possible and cannot be larger than 150 cm due to the wind turbine geometrical limitations [9]. The photos of the HG and LG antennas for experiments are provided in Fig. 8 (c). The measured gain of both antennas is around 1-1.5 dBi lower than the simulated. The root antenna (receiver) is a horn antenna with high gain, which is shown in Fig. 8 (d). Both the horn antenna and tip antennas can sufficiently cover the UWB band of 3.1-5 GHz with the specification of −10 dB reflection coefficient.

The input pulse is generated from a UWB pulse generator with the frequency bandwidth of 3.1-5 GHz. The input pulse waveform is provided in Fig. 9. Only the rising edge of the input pulse is used as the template, which is more robust to the multipath interference. The template will be compared with the output pulse waveforms for distance estimations.

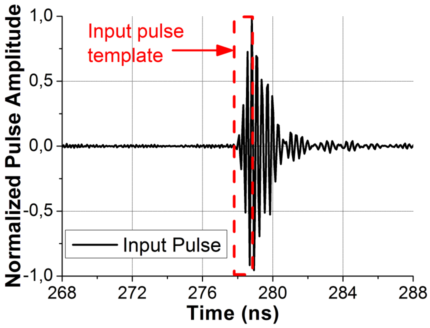


FIGURE 9. Measured input pulse waveform.

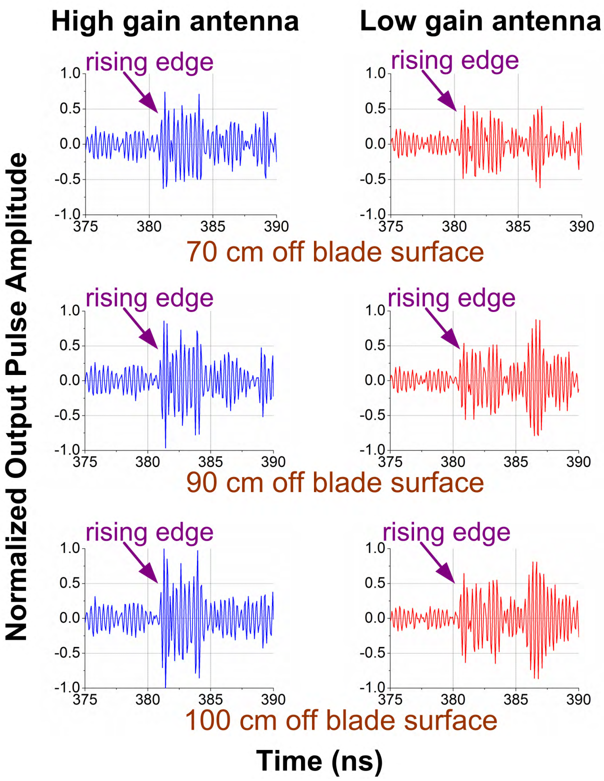


FIGURE 10. Measured normalized output pulse waveforms above downwind surface with the high gain and low gain antennas.

The measured output pulse waveforms above the downwind surface and leading edge are shown in Fig. 10 and Fig. 11, respectively. The pulse amplitudes in Fig. 10 and Fig. 11 are normalized according to the maximum amplitude in the measurement 100 cm off the blade downwind surface and with the HG antenna. Since the pulse amplitudes above the leading edge are relatively weaker than those above the downwind surface, the heights of the root antenna in the leading edge cases are chosen to be a little higher. The phenomena observed in Fig. 10 and Fig. 11 are very similar to those in the simulations. The HG antenna enlarges the amplitudes of both the direct (or first) pulse and multipath pulses. The HG antenna also makes the direct pulse more distinguished from multipath pulses than the LG. The HG antenna can

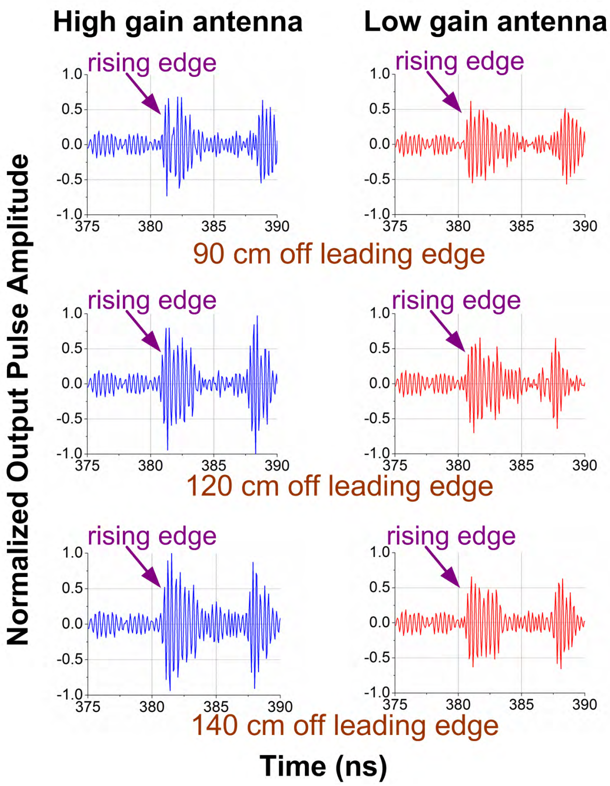


FIGURE 11. Measured normalized output pulse waveforms above leading edge with the high gain and low gain antennas.

significantly improve the quality of pulse waveforms for distance estimations.

In order to further investigate the accuracy of distance estimations using the antennas with different gains, the correlation method in [15] has been utilized. The correlations are calculated between the input pulse template (in Fig. 9) and output pulses (in Fig. 10 and Fig. 11). Correlator's cost functions are generated and the estimates are extracted as a minimum. In Fig. 12 (a), the estimated time delays with the measured pulse waveforms are shown for the measurements above the downwind (DW) surface and the leading edge (LE). The time delays in Fig. 12 (a) include the delay in the long feeding cable and in the air. In all the measurements, the feeding cable length is kept the same. Furthermore, the phase centers of the HG and LG antennas are difficult to be placed at exactly the same position during all the experiments. However, the difference of tip-root antenna distances between two root antenna heights should be similar in the HG and LG cases. It means that in Fig. 12 (a) the curves of the HG and LG above DW should be parallel with each other if the distance estimations are accurate. Similarly, the curves of the HG and LG above LE should also be parallel with each other. In addition, geometrically, the tip-root antenna distance above LE is shorter than that above DW. For the LG antenna in Fig. 12 (a), the distance estimation of 70 cm off the DW is wrong, and the estimations above leading edge are delayed for all the root heights. These errors and delays are

TABLE 2. Accuracy investigations with a high gain or low gain antenna.

	downwind surface	
	root antenna height from 70 cm to 90 cm	root antenna height from 90 cm to 100 cm
Δd if dz =32 m	10.9 mm	5.9 mm
Δd if dz =33 m	10.6 mm	5.8 mm
estimated Δd with HG	10.8 mm	5.4 mm
estimated Δd with LG	49.5 mm	5.4 mm

dz is tip-root antenna distance in z-axis direction. Δd is the difference of the tip-root antenna distances between two root antenna heights.

mainly due to the weak and interfered direct pulse rising edge of the LG antenna. For the HG antenna, all the estimations are correct. Fig. 12 (b) shows the difference between the minimum and the second minimum values in correlator's cost function. The larger difference indicates the system has less chance to track on the wrong pulse and the reliability of the estimation is higher. The negative value of δ means the wrong and delayed estimations. In general, the δ in the HG case is always better than that in the LG case.

From our studies, in this system, the error in a distance estimation will be approximately translated into a 10-time larger error in deflection sensing. If we can check the accuracy of distance estimations, it is also possible to estimate the errors in deflection tacking. In the measurements of this paper, the actual tip-root antenna distances are difficult to obtain, since a laser range founder cannot reach the in-blade tip antenna directly due to the blade shell blockage. However, the tip antenna locations are kept the same during the downwind-surface (or leading-edge) measurements. The accuracy of distance estimations above downwind surface can be verified in another way: the tip-root antenna distance in z-axis direction is between 32 m and 33 m, and the diameter of the blade root is 1.89 m. Since a straight blade (as well as the tip antenna in it) is approximately symmetrical in xz plane (see Fig. 2 (a)), the tip-root antenna distance in y-axis direction can be obtained. In Table 2, dz is the tip-root antenna distance in z-axis direction. The Δd is the difference of the tip-root antenna distances between two root antenna heights. It can be seen clearly that the estimated Δd with high gain is always close to the actual Δd if dz $= 32$ m or dz $= 33$ m, which indicates high accuracy in the deflection sensing with a HG tip antenna. In addition, since the straight blade (as well as the tip antenna in it) is not symmetrical in yz plane (see Fig. 2 (a)), the tip-root antenna distance in x-axis direction is unknown. The results above the leading edge cannot be calculated and involved here.

B. SETUPS AND RESULTS OF PULSE POWER DELAY PROFILE MEASUREMENTS

The power delay profiles are also measured for the HG and LG antennas. The measurement setups can be observed in Fig. 13 (a). The tip antenna is placed inside the blade.

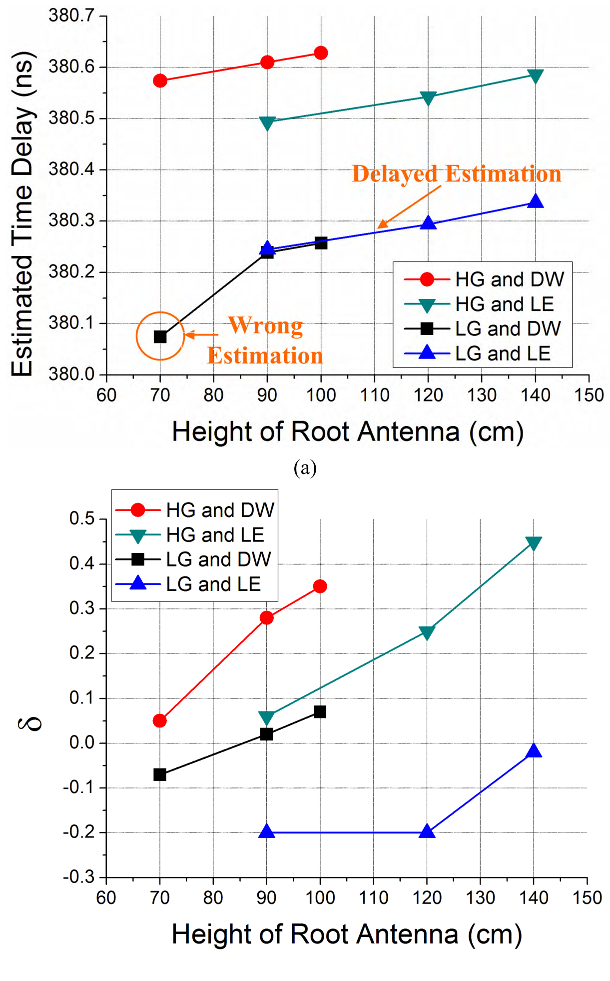
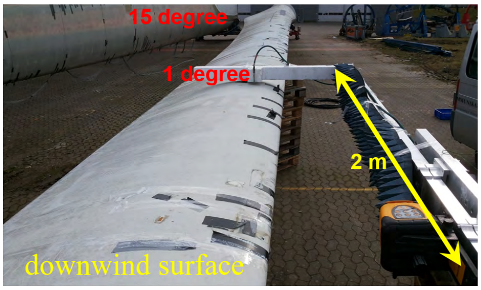
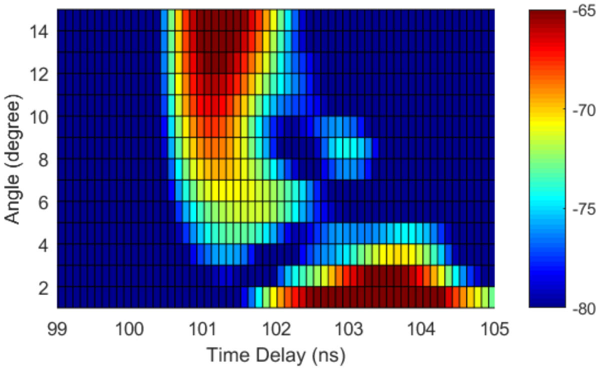


FIGURE 12. (a) Estimated time delay with measured pulse waveforms, (b) the difference between the minimum and the second minimum values in correlator's cost function.

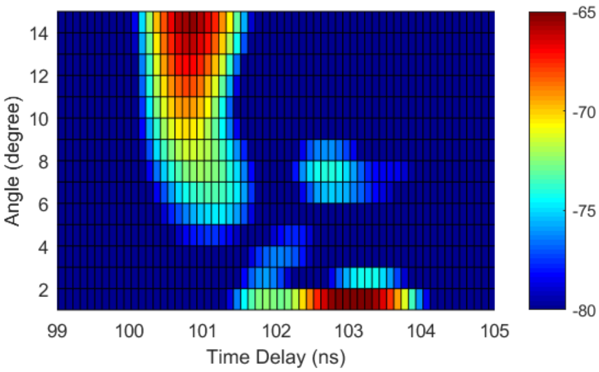
A 2-meter long scan arm is used with one end fixed at the tip antenna location and the other end scanning from 1 degree to 90 degree. A signal is generated by a network analyzer, and then transmitted from the in-blade tip antenna. The signal is received by a UWB probe antenna at the end of the scan arm. The probe antenna has the gain of over 2 dBi and the bandwidth of 3.1-5 GH. Kaiser Window [16] is applied in the Fourier transform to change the measured frequency domain data (in 3.1 −5 GHz) into the time-domain. From 1 degree to 90 degree, the strongest pulse power for HG and LG antennas inside a blade are −63.4 dB and −64.1 dB, respectively. This has also verified that both antennas have the similar realized gain when placed inside the blade. The measured pulse power delay profiles for the HG and LG antennas are shown in Fig. 13 (b) and Fig. 13 (c) within -15 degree, respectively, (since in different deflections the root antenna can only receive the power transmitted by a tip antenna within 15 degree). The direct pulse with the HG antenna is stronger and closer to the blade surface than the one with the LG. Although the surface waves in HG are also



(a)



(b)



(c)

FIGURE 13. Pulse power delay profile measurements: (a) measurement setups, (b) pulse power delay profile of the high gain antenna, and (c) pulse power delay profile of the low gain antenna.

enhanced, the rising edge of the direct pulse is not distorted by them.

IV. CONCLUSIONS

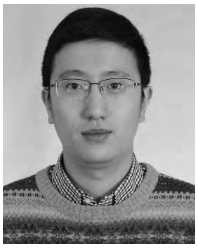
This paper has investigated antenna gain impact on UWB wind turbine blade deflection sensing. Simulations have been performed with a 4.5-meter blade tip section. The maximum transmitting power of a sensing system is directly related to the gain of a tip antenna due to the EIRP limitations. The realized gain with the tip antenna inside the straight or deflected blade has been simulated in the frequency domain. The HG and LG antennas have similar realized gain when allocated in blades, so the transmitting power for the HG and LG antennas in blades can be set the same. Simulations have also been performed to study the antenna gain impact on pulse waveforms and power distributions. To verify the tendencies obtained from the simulations, time-domain measurements have been carried out with a 37-meter blade. Pulse waveforms have been measured and evaluated above both downwind surface and leading edge. In-blade tip antenna with HG gives the better direct pulse amplitude and pulse waveforms than the antenna with LG. Due to the strong and good pulse quality, the case with the HG antenna has better accuracy and reliability in distance estimations. Pulse power delay profiles have also been measured above downwind surface with a 2-meter scan arm. The direct pulse with the HG antenna is stronger and closer to the blade surface than the one with the LG. In practical applications, an HG antenna should be applied when a tip antenna is placed inside a blade. The HG can also help improve UWB signal quality in different lengths of blades (e.g. 60m blade or longer blades).

ACKNOWLEDGMENT

The authors would like to thank LM Wind Power for providing the full-blade measurement equipment used in this paper.

REFERENCES

[1] K. Papadopoulos, E. Morfiadakis, T. P. Philippidis, and D. J. Lekou, "Assessment of the strain gauge technique for measurement of wind turbine blade loads," *Wind Energy*, vol. 3, no. 1, pp. 35–65, 2000.
[2] E. Udd, "Fiber optic smart structures," *Proc. IEEE*, vol. 84, no. 6, pp. 884–894, Jun. 1996.
[3] M. Moradi and S. Sivoththaman, "MEMS multisensor intelligent damage detection for wind turbines," *IEEE Sensors J.*, vol. 15, no. 3, pp. 1437–1444, Mar. 2015.
[4] K. A. Kragh, M. H. Hansen, and L. C. Henriksen, "Sensor comparison study for load alleviating wind turbine pitch control," *Wind Energy*, vol. 17, no. 12, pp. 1891–1904, 2013.
[5] P. Giri and J.-R. Lee, "Development of wireless laser blade deflection monitoring system for mobile wind turbine management host," *J. Intell. Mater. Syst. Struct.*, vol. 25, no. 11, pp. 1384–1397, 2014.
[6] Z. N. Chen, "UWB antennas: Design and application," in *Proc. 6th Int. Conf. Inf., Commun. Signal Process. (ICICS)*, Singapore, Dec. 2007, pp. 10–13.
[7] R. Bharadwaj, C. G. Parini, and A. Alomainy, "Experimental investigation of 3-D human body localization using wearable ultra-wideband antennas," *IEEE Trans. Antennas Propag.*, vol. 63, no. 11, pp. 5035–5044, Nov. 2015.
[8] M. Fantuzzi, D. Masotti, and A. Costanzo, "A novel integrated UWB–UHF one-port antenna for localization and energy harvesting," *IEEE Trans. Antennas Propag.*, vol. 63, no. 9, pp. 3839–3848, Sep. 2015.
[9] S. Zhang *et al.*, "UWB wind turbine blade deflection sensing for wind energy cost reduction," *Sensors*, vol. 15, no. 8, pp. 19768–19782, 2015.
[10] S. Zhang and G. F. Pedersen, "Compact wideband and low-profile antenna mountable on large metallic surfaces," *IEEE Trans. Antennas Propag.*, vol. 65, no. 1, pp. 6–16, Jan. 2017.
[11] S. Zhang, T. L. Jensen, O. Franek, P. C. F. Eggers, C. Byskov, and G. F. Pedersen, "Investigation of a UWB wind turbine blade deflection sensing system with a tip antenna inside a blade," *IEEE Sensors J.*, vol. 16, no. 22, pp. 7892–7902, Nov. 2016.
[12] S. Zhang, O. Franek, P. C. F. Eggers, C. Byskov, and G. F. Pedersen, "Multipath suppression with an absorber for UWB wind turbine blade deflection sensing systems," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 7, pp. 2583–2595, Jul. 2017.
[13] *Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems Report and Order*, document DA-02-1658, Federal Communications Commission, Jul. 2002.
[14] *LM Wind Power*. Accessed: Apr. 5, 2018. [Online]. Available: http://www.lmwindpower.com
[15] C. H. Knapp and G. C. Carter, "The generalized correlation method for estimation of time delay," *IEEE Trans. Acoust., Speech Signal Process.*, vol. 24, no. 4, pp. 320–327, Aug. 1976.
[16] J. F. Kaiser, *System Analysis by Digital Computer*. New York, NY, USA: Wiley, 1966, ch. 7.



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