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Wind Turbine Blade Deflection Sensing System Based on UWB Technology

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Abstract—**A microwave sensing system for estimating deflection of a wind turbine blade is presented. The system measures distances at two ultrawideband (UWB) wireless links between one antenna at the tip and two antennas at the root of the blade, which allows for determination of the tip position by triangulation. An experimental setup with corner reflector antenna mounted at the tip and horn antennas at the root of a 37.3 m long blade is described. Analyzing the data from the experiment, special attention is given to the propagation aspects of the UWB links, with focus on the multipath effects caused by the blade. It is demonstrated that despite the adverse effects of the multipath propagation the ranging accuracy of the system amounts to 1.5 cm, leading to maximum error of deflection 4.5 %.**

1 INTRODUCTION

With the increasing awareness to green and sustainable power generation and focus on reducing dependence on fossil fuels, wind energy is considered as one of the key enabling factors that has been proven by decades of reliable operation. Harvesting as much energy as possible from a single wind turbine can be achieved by installing longer blades which cover larger area of the wind field. However, longer blades pose a danger of tower strike at high wind loads due to their elasticity. If reliable measurement of blade deflection was available, the turbine could be operated at higher wind speeds and resort to pitching or even performing an emergency stop whenever tower strike is imminent.

The most widespread means of measuring blade deformation is using strain sensors utilizing fiber Bragg gratings [1], although their operational deployment is not straightforward due to extensive calibration requirements. Another possibility is offered by MEMS-based accelerometers and gyroscopes [2], but their application is problematic as they are vulnerable to induced effects of nearby lightning strikes. Further options include laser-based ranging equipment mounted at the tower or nacelle [3], it is, however, not clear yet to what degree these systems will be affected by low visibility weather conditions such as thick fog.

In this contribution, we present a microwave sensing system that uses ultrawideband (UWB) pulse technology to estimate the position of the blade tip and therefore its deflection [4]. Main focus is given to the multipath effects and distortion of the UWB pulse caused by propagation of the wave along the fiberglass-air boundary.

2 SYSTEM DESCRIPTION

The deflection sensing system is designed to be consisting entirely of parts attached to the blade and working independently from the nacelle and the tower, therefore there are three independent systems on each blade of the wind turbine. Each system consists of one TX antenna mounted at the tip of the blade and two RX antennas near the blade root (Fig. 1). By accurately measuring distances at these two wireless links, and assuming that due to stiffness of the blade bending occurs mainly along a single plane, we can determine the deflection by triangulation. However, the chosen approach poses several challenges:

2.1 Antennas

The wireless link between the tip and the root does not always follow line-of-sight conditions as the blade can be bent both in upwind (away from the tower) and downwind (towards the tower) directions. In addition, there is a fundamental limitation in that the root antennas cannot be elevated too far from the blade surface due to the tower clearance which is typically less than 1.5 m. To increase the chance of successful detection, and to increase the robustness of the triangulation, two antennas are placed at the blade root, thus forming two wireless links.

The tip antenna needs to have very low profile if placed outside of the blade due to aerodynamic reasons—the blade tip can travel at speeds up to 90 m/s and even a small protrusion on the surface of the blade will cause aerodynamic noise and decrease efficiency. If the antenna is placed inside, the fiberglass blade shell obstructs the channel and causes losses due to reflections at low angles.

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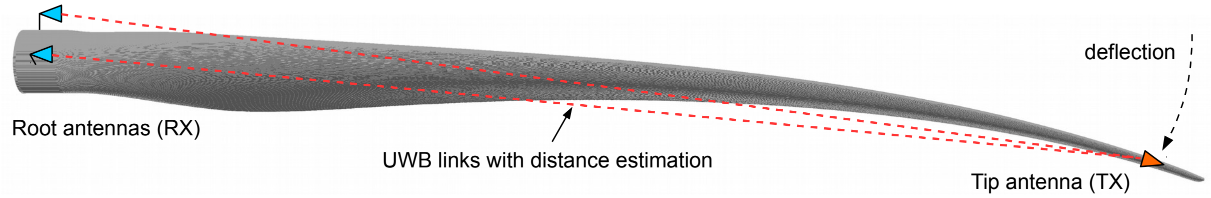

Figure 1: Schematic drawing of the UWB blade deflection sensing system.

2.2 Multipath effects

Since the wireless link is mostly parallel to the blade, the channel suffers from multipath effects. One of the distinct mechanisms is the surface wave that is formed near the tip antenna and propagates along the blade surface towards the root. Despite being attenuated, it contributes to the radiation by gradual leaking and eventually distorts the received pulse, causing problems with time-of-arrival (TOA) estimation.

2.3 Component hardening

Both antennas must withstand harsh climatic conditions, rain, freezing temperatures, and dynamic stresses for the entire life span of the blade. Especially important is the protection of the antennas, cabling inside the blade, and the radio equipment from direct lightning strikes and induced effects.

2 EXPERIMENTAL SETUP

The setup utilized a 37.3m long wind turbine blade mounted in a test center with pulling clamp attached to provide simulated deflection from –1.0 to 1.5 m (Fig. 2). At the root, we installed EMCO 3115 wideband horns with gain 8.5–11 dBi as RX antennas [5]. We scanned across various positions on the mounting brackets to find the best reception point from 3 criteria: a) minimum of shadowing effects for most deflections, b) maximum separation for improved accuracy of triangulation, and c) minimum multipath components due to surface wave pickup at low heights. The optimum positions turned out to be at angle –15.5° and height 1.07 m for root antenna A (in Fig. 3 on the right), and at angle 18.3° and height 0.6 m for root antenna B (in Fig. 3 on the left). The apparent asymmetry of the resulting positions is due to asymmetric shape of the blade itself.

At the tip, a monopole antenna with corner reflector served as TX antenna, featuring 7 dBi gain and stable phase center. The tip antenna was mounted on the leading edge outside of the blade 3 m from the tip, in front of the pulling clamp (Fig. 4), in order to ensure possibly the least obstructed view of the root antennas. It should be noted, however, that this position was chosen for testing purposes only. In practical application the antenna would need to be

Figure 2: The 37.3m wind turbine blade in the experimental setup; the pulling clamp is mounted near the tip; the RF absorbers are visible at mid-way to the root.

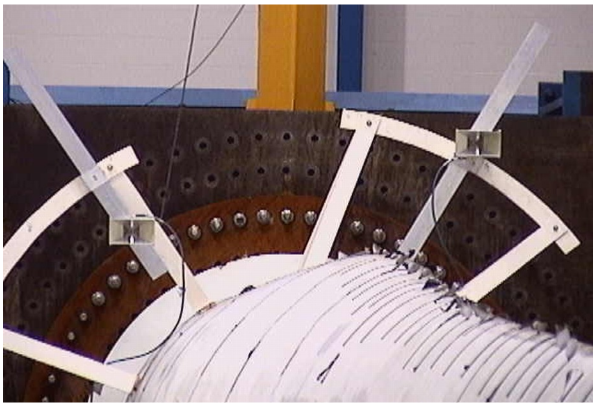

Figure 3: Root antennas mounted on brackets: root A on the right, root B on the left.

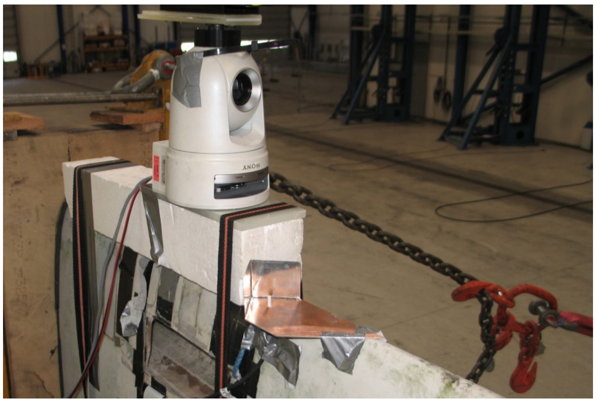

Figure 4: Tip antenna and the laser range finder with camera mounted in front of the pulling clamp.

placed in a radome, and even then it would most likely contribute significantly to increased aerodynamic drag and noise.

The TimeDomain P410 [6] UWB radio generated pulses in the frequency range 3.1–5.3 GHz with sampling period 6.1×10^{-11} s. The detection of the rising edge of the received pulse was performed with external algorithm implementing maximum a posteriori (MAP) estimator, which is an improved adaptive correlator [7]. To compare the UWB distance estimates, a laser based range finder Leica D8 was installed near the tip TX antenna (visible in the upper part of Fig. 4).

3 RESULTS

The UWB radio outputs for the described experimental setup are shown in Fig. 5. The rows of the figure present three chosen blade deflections, –1.0 (prebend, direction to the right in Fig. 2), 0.0 (straight) and +1.0 m (operational deflection, direction to the left in Fig. 2), whereas the columns correspond to signals at the root antennas A and B, respectively. The line-of-sight (LOS) pulses arriving first and the late-arriving multipath components are apparent. It can be seen that the LOS pulses tend to be strong when the path between the TX and RX antennas is unobstructed, as opposed to situations when the wave travels parallel to the lossy material of the blade edge.

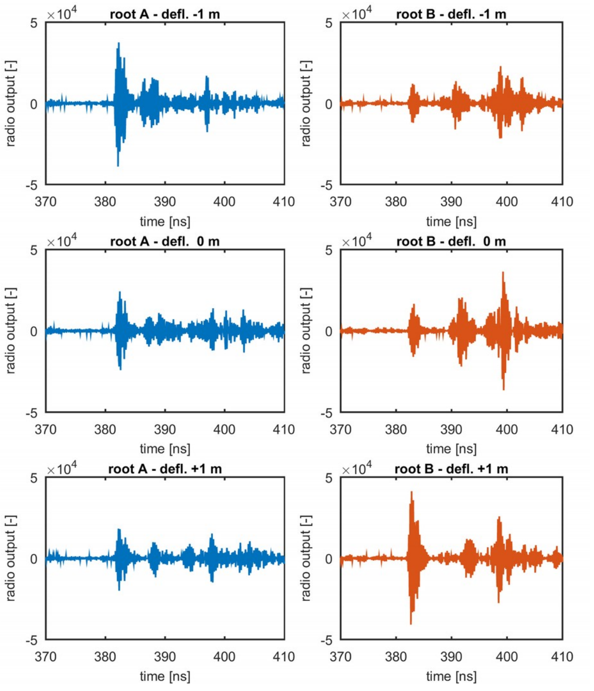

Figure 5: UWB radio output signals at the root antennas A and B (columns), for deflections –1.0, 0.0, +1.0 m (rows)

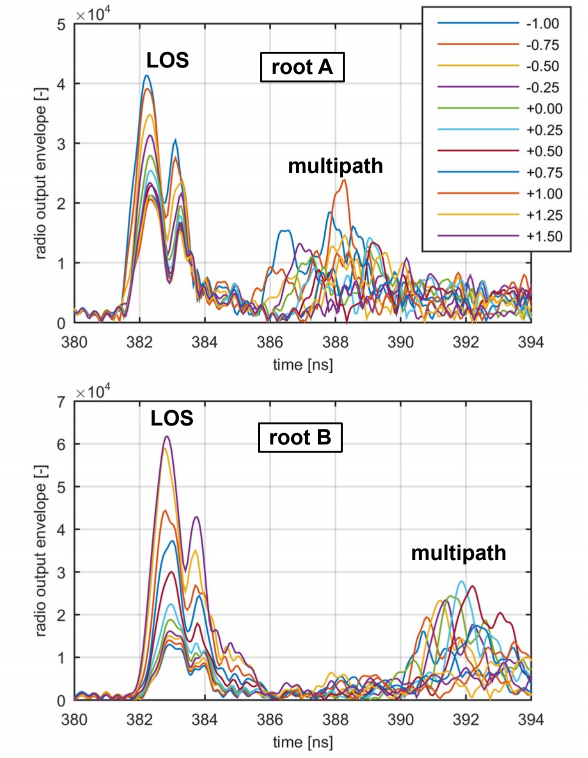

Figure 6: Radio output envelopes at root antenna A (above) and B (below) for various deflections [m].

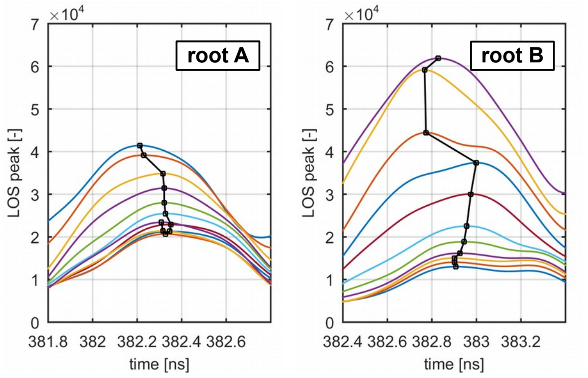

Figure 7: Details of Fig. 6 with the positions of the LOS peaks.

The first multipath component (see Fig. 6) is probably caused by reflection from the wall, as it comes significantly later (9 ns) on root B antenna than on root A (6 ns)—the corresponding orthogonal distances of the scatterer are 5.5 and 6.8 m for root A and root B, respectively. Reflections from the floor were intentionally suppressed by placing RF absorbers mid-way from the tip to the root (Fig. 2). However, these reflections are relatively harmless, because they do not interfere with the LOS pulse.

More problematic is the surface wave on the blade edge near the tip antenna which partially distorts the LOS pulse. As can be seen in detail in Fig. 7, the peak of the LOS pulse fluctuates irregularly and cannot be used as an indication of TOA.

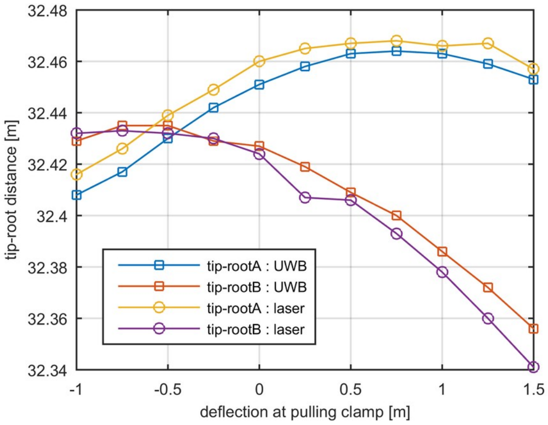

Figure 8: Comparison of the UWB and laser based distance estimations [4].

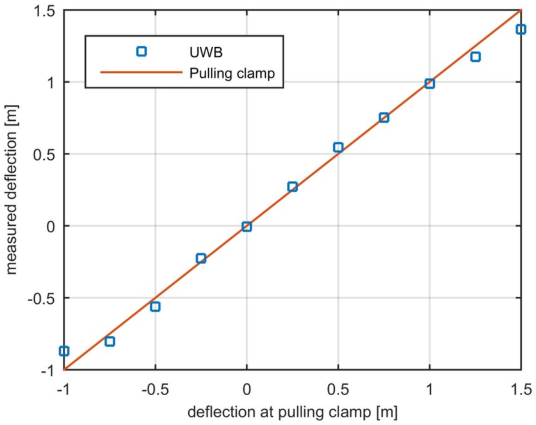

Figure 9: UWB measured deflection compared to the measured deflection at the pulling clamp.

Instead, the distance of the tip was determined by TOA of the rising edge of the first pulse arriving at the RX. This value was compared with laser range finder mounted on the clamp and measuring concurrently with the UWB system; the distances matched within 1.5 cm of accuracy, resulting in maximum error of deflection 4.5 % after triangulation (see Figs. 8, 9).

4 CONCLUSIONS AND FUTURE WORK

It has been demonstrated that the presented deflection sensing system is capable of providing sufficient accuracy for field deployment. However, it should be noted that the positive results have been achieved using the corner reflector antenna mounted outside the blade and this solution is not desirable from aerodynamic point of view.

In the next iteration of the experiment, we placed the tip antenna inside the blade, where it does not disturb the air flow around the blade and is protected against adverse weather effects. The penalty of this approach turned out to be around 30 dB of added channel loss due to reflection from the blade shell at shallow angle, and also added multipath effects due to propagation inside the blade and stronger excitation of the surface wave on the shell.

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