Radar-based Structural Health Monitoring of Wind Turbine Blades

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Abstract. Millimeter-wave and terahertz technology have been used successfully in non-destructive testing (NDT) applications in order to identify material defects such as delamination, heat damages and inclusions. The contribution of this paper is to extend the millimeter-wave and terahertz technology from a classical NDT methodology towards a continuous structural health monitoring (SHM) approach. For the first time, we will propose a scalable radar-based SHM-concept for operating wind turbine blades, where the transmitting and receiving antennas are placed at the tower and the antennas radiate the electromagnetic waves towards the rotor blades. Exploiting the rotation of the wind turbine and therewith a synthetic aperture with regard to the ISAR (inverse synthetic aperture) principle, all blades can be inspected with a sensor array in a non-contact and highly automated way. This approach has economic relevance not only for new but also for ageing wind turbine structures.

Additionally, the same radar sensor can be applied for the detection of bat and bird activities close to the wind turbine which is highly relevant for the permission to operate existing and newly installed turbines. Based on the evaluation of the condition status of the turbine and the knowledge of the instantaneous bat and bird activity, new and harmonizing concepts for the operation of wind turbines can be established that account for the demands of the wind turbine operator (and hence public energy supply) as well as the protection of nature.

This paper focuses on the frequency bands 24 - 24.25 GHz and 24 - 25.6 GHz which allow a high penetration depth in glass-fiber reinforced materials. Simulation results will be presented that illustrate the concept of differential radar imaging of material defects. Moreover, an experimental proof of principle study is presented from transmission measurements of a rotor blade tip sample of a real wind turbine structure.
1. Introduction

According to the Global Wind Energy Council the global wind capacity has reached about 370 GW at the end of 2014 compared to about 198 GW at the end of 2010 [1]. These numbers show the importance of wind energy for the generation of electrical power by means of renewable sources worldwide. However, in order to guarantee reliable wind power generated by onshore and offshore platforms it is important to provide efficient maintenance strategies that are able to detect structural degradation reliably and online during wind turbine operation. Therefore, many different techniques have been proposed such as vibration or strain monitoring, acoustic emission testing etc. [2].

There are a number of review articles that study condition monitoring (CM) and structural health monitoring (SHM) systems for the assessment of damage in wind turbine structures [2]–[5]. Interestingly, approaches related to radar (or high-frequency electromagnetic radiation in general) are not discussed in these papers yet. On the other hand, many examples for the non-destructive inspection of material defects at microwave, millimeter-wave and terahertz frequencies have been published in the literature [6]. The goal is to find material imperfections, such as delaminations or inclusions, after image processing by means of manual [7], [8] or semi-automatic analysis [9]. Moreover, interferometric radar methods for vibration sensing of civil structures are reported in [10].

In the literature, few studies have been published that use Doppler radar measurements for vibration sensing in CM and SHM applications. An example is given by a microwave sensor in [11] that is used for tip clearance monitoring in gas turbines. A Doppler radar for measuring vibrations before and after damage injection behind a barrier material consisting of polystyrene foam at 100 GHz is demonstrated in [12]. Moreover, a portable continuous wave sensor with automatic DC-calibration for SHM applications is presented in [13].

The novelty of this contribution is the introduction of radar technology as a new modality for structural health monitoring of wind turbine blades. Therefore, the transmitting and receiving antennas are placed along the tower of the wind turbine, as depicted in Fig. 1, and the antennas radiate the electromagnetic waves towards the rotor blades. Exploiting the rotation of the wind turbine and therewith a synthetic aperture with regard to the ISAR (inverse synthetic aperture) principle, all blades can be inspected with a sensor array in a non-contact and highly automated way. This approach has economic relevance not only for new but also for ageing wind turbine structures.

Additionally, the same radar sensor can be applied for the detection of bat and bird activity close to the wind turbine which is highly relevant for the permission to operate existing and newly installed turbines [14], [15]. Based on the evaluation of the condition status of the turbine and the knowledge of the instantaneous bat and bird activity, new and harmonizing concepts for the operation of wind turbines can be established that account for the demands of the wind turbine operator (and hence public energy supply) as well as the protection of nature.
2. Challenges of damage detection in wind turbine blades

Rotor blades seem to be the most important components of wind turbine structures [4]. Their testing is difficult due to the large dimensions of many tens of meters. On the other hand, a blade failure is costly, because it can damage other blades of the same wind turbine or other wind turbines in the proximity. The authors in [4] conclude that future maintenance systems require non-contact and remote non-destructive inspection technologies that have “overwhelming advantageous in online testing and inspection”. Radar technology as presented here, seems to be one of the promising modalities in that sense.

At present, several sensor concepts for CM and SHM of wind turbine structures exist. The authors in [5] make the distinction between the inspection of blades, rotor, gearbox, generator, bearings and tower. The most relevant techniques for the monitoring of blades are given by vibration analysis, acoustic emission, ultrasonic techniques, strain, electrical effects, and the monitoring of process parameters. Besides damage detection it is also relevant to consider the detection of ice on the rotor blades [16].

Using radar technology it is possible to determine an image of the rotor blade by means of differential signal processing, i.e. the radar signal of the pristine structure is subtracted from the corresponding radar signal from the damaged structure (demonstrated by the authors with a laboratory model of a wind turbine in [17]). This differential signal is the input for the subsequent ISAR image processing which can be used for damage assessment and alarming. Although the radar approach is promising for the inspection of many dielectric materials used in the blade design, it is limited in terms of rotor blades consisting of electrically conducting carbon fiber reinforced (CFR) laminates. In these composite materials, the penetration of electromagnetic radiation is limited so that material defects inside the structure cannot be detected. However, as soon as the damage grows and affects the shape of the blade surface these changes can be measured. Since the fabrication of turbine blades made of CFR-material
is more expensive than glass fiber reinforced (GFR) material, the large majority of rotor blades from small to middle sized turbines consists of GFR-materials [18].

3. Results

3.1 Simulation results for differential radar-based defect imaging in rotor blades

The concept of differential signal processing is very common in Lamb wave SHM-applications, compare for example [19]. It is also used in biomedical radar applications [20]. The same concept can also be applied in radar-based SHM, where the reference measurement from the pristine structure is subtracted from the current measurement. In the idealized case of two consecutive measurements the differential signal is almost zero and contains only measurement noise. When changes of the signal occur then these can be clearly observed in the corresponding differential signal.

Fig. 2 illustrates this idea based on simulated signals in which point targets are used to model the front wall, the back wall and also a defect in the structure. The front wall and the back wall echoes can be clearly seen in the image reconstruction (strong reflectors) and the defect is only barely visible. Damage detection is even more complicated when the defect occurs close to the front or back wall. In that case the contrast is negligible and the damage detection sensitivity rather low. In case of differential signal processing the damage can be de-embedded and clearly identified in the corresponding differential image.

3.2 Experimental proof of principal study using a real rotor blade sample

3.2.1 Description of the experimental setup

The experimental setup used in this paper consists of a point-to-point measurement through a rotor blade tip sample of GFR material as shown in Fig. 3. The horn antennas of the transmitting and receiving antennas are placed on opposite sides each having an air gap to the sample. The basic idea is to place different materials inside the rotor blade at the inspection area and to evaluate the changes in the signals.
3.2.2 Radar Sensor

The used radar device is a newly developed frequency-modulated continuous-wave radar (FM-CW radar). The concept of these systems is based on a well-known frequency modulation scheme for time of flight (TOF) calculations. The FM modulation is designed as a continuous transmitting wave with linearly increasing frequency. Simultaneously, the same frequency is used as a reference in the receive chain for heterodyne mixing. Thus, time delayed echoes provide an intermediate frequency (IF), i.e. the difference between transmitted and received frequency, which is proportional to the TOF and therewith provides a range information [1].

The used radar chip is an Infineon Silicon Germanium MMIC (BGT24MTR12) which is readily available for the mass market. Main features are an operation frequency range between 24 and 26 GHz, with a fully integrated low phase noise voltage controlled oscillator (VCO), a high conversion gain of 26 dB and a low power consumption of 660 mW. Detailed specification are available in public data sheets. The frequency sweep time for the experiments are set to 50 µs which offers an adequate compromise between unambiguous range and accuracy.

Obviously, two significant requirements in an FM-CW Radar are linearity and low phase noise. Especially for highly precise range extractions the achievable precision directly depends on the linearity of the frequency sweep since erroneous frequency values directly cause deviations in the mixing operation. A phase-locked loop (PLL) based system with an 8 GHz fractional synthesizer is used to meet the requirements on linearity of the frequency sweep and phase stability. Details on PLL techniques can be found in [2]. The horn antennas in the experiments have a high gain of approximately 24 dBi.

The IF output signal from the mixer is sampled by an A/D converter for subsequent signal processing. The used A/D has 16 bit resolution and a maximum sampling frequency of 20 MSPS for 2 channels. The radar module is controlled by an Artix FPGA from Xilinx. This makes it possible to easily change the bandwidth of the system by software modification. In this study, we have considered two different frequency bandwidths, i.e. 24-25.6 GHz (B₁: 1600 MHz) and 24-24.25 GHz (B₂: 250 MHz), respectively. The I- and Q-channels of the

**Fig. 3.** Experimental setup for proof of principle tests: rotor blade tip sample of GFR-material (left) empty; (right) a bottle of water (to simulate water in the blade tip) placed between the antennas.
radar module are forwarded to a PC via ethernet communication for further analysis. With this radar module it is possible to record approximately 8,000 measurements per second using Matlab® software.

3.2.2 Results

Three different transmission measurements for both frequency bandwidths have been performed. First, the rotor blade sample is measured alone. Next, a bottle of water is placed in the rotor blade to simulate water in the blade tip as depicted in Fig. 3. Water in the blade tip is a relevant source for blade damage, because it turns into steam during a lightning event [21]. This leads to delamination, cracking, debonding or spar separation. Finally, a metal plate is placed inside the blade. The goal of these measurement was to find changes in the range profiles with respect to the pristine state of the blade sample. The measurement time was one second and all measurements were averaged for optimal signal-to-noise ratio.

The results are illustrated in Fig. 4 and show the range profiles for the larger bandwidth on top and the signals for the lower bandwidth at the bottom. The first finding is that it is possible in both cases to measure the millimetre-wave signal through the whole blade sample. Otherwise no signal could be measured with the proposed point-to-point antenna arrangement. As soon as the bottle of water is placed in the wave propagation path, a significant drop in amplitude can be observed. This result shows nicely that water can be easily detected in a realistic GFR rotor blade sample when the reference state of the dry blade is known. This information is typically available in SHM-applications. Moreover, when a metal plate (radiation blocker) is placed in the wave propagation path, then the signal amplitude drops even further. A small signal can still be measured, due to the fact that the plate is of finite size and multipath propagation cannot be avoided completely. When comparing both frequency bandwidths one can find significant differences in the resolution of the signal. The reason therefore is related to the fact that the bandwidth of the signal is inversely related to its range resolution. This leads to two peaks for the larger and only a single peak for the smaller bandwidth due to multipath propagation inside the blade sample.

![Fig. 4. Comparison of transmission measurements through the rotor blade sample at two different bandwidths; (top) B₁=1600 MHz; (bottom) B₂=250 MHz.](image-url)
4. Conclusions

This paper introduced a radar-based structural health monitoring concept for wind turbine structures in which a damage can be detected by means of differential signal processing. Radar simulations are used to illustrate the basic differential approach, supported by transmission measurements using a glass fiber reinforced rotor blade tip sample. It was found that a full penetration through the rotor blade is possible at 24 GHz and water can easily be detected. An experimental comparison has been performed using two different bandwidths, i.e. 24-25.6 GHz (B₁: 1600 MHz) and 24-24.25 GHz (B₂: 250 MHz). In a next step, reflection measurements using a laboratory demonstrator of a wind turbine will be studied [17].

Acknowledgement

This work is part of the B2-Monitor project "Millimeter-Waves for Monitoring Bats and Blades" and has been supported by the Federal Ministry for Economic Affairs and Energy (grant number: FKZ 0325791A). More information can be found at http://www.b2monitor.de.

References


