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Structural Health Monitoring of Wind Turbine Blades using Radar Technology: First Experiments from a Laboratory Study

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Abstract

Millimeter-wave and terahertz technology have been used successfully in non-destructive testing (NDT) applications. While being safe for human beings and animals, a high resolution imaging in a non-contact and non-destructive way is possible due to the short underlying wavelength. The contribution of this paper is to demonstrate, for the first time, that imaging radar systems can be used effectively for structural health monitoring (SHM) purposes. For validation reasons, we have developed a laboratory demonstrator of a wind turbine structure for millimeter-wave measurements of rotating samples, with which we investigated glass-fiber samples. Hereby we can adjust the rotor speed, pitch and vertical incline angle. The radar sensor is attached to a nearby platform and mounted on a linear motor stage. This allows us to scan a rotating sample in vertical direction. The focus of our contribution is to demonstrate the feasibility of the radar-based SHM-concept with experimental measurements in order to investigate typical defects in rotating glass-fiber materials in the frequency band of 24-25.6 GHz. With our setup, we are able to identify typical defects of rotor blades.

1 INTRODUCTION

A number of review articles study condition monitoring (CM) and structural health monitoring (SHM) systems for wind turbine structures [1]–[4]. 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 [5]. The goal is to find material imperfections, such as delaminations or inclusions, after image processing by means of manual [6], [7] or semi-automatic analysis [8].

This paper proposes a radar-based methodology for the SHM of wind turbine blades in the frequency band of 24-25.6 GHz. This band seems to be a good compromise in terms of resolution and penetration depth. The remainder of this paper is organized in the following way: Section 2 presents the experimental setup including the mechanical setup of the laboratory system and the radar sensor device. After that three case studies will be reported and discussed that include the detection of artificial damage, the detection of dirt on the surface of the rotor blade as well as the impact of temperature on the radar signals. Finally, conclusions are drawn at the end.

2 EXPERIMENTAL SETUP

2.1 Description of the Mechanical Setup

For the first laboratory experiments, we developed a demonstrator of a wind turbine structure. The demonstrator consists of a rotary stage in the horizontal direction (Figure 1) and a linear motor stage in vertical direction with a mounted radar sensor.

The rotary stage was designed such, that samples with a weight of up to 70 kg can be rotated at a frequency of up to 1 Hz. In addition the pitch and vertical incline angle could be adjusted freely. For the precise control of the rotor speed, we used the Beckhoff servor motor AM8542. On the rotor stage, we can mount up to 10 mm thick glass fiber reinforced (GFR) samples, dummy rotor blade but also the tip of a real rotor blade sample. For the vertical motion of the radar sensor, we used a Beckhoff AL2406 linear servomotor. The synchronized motion control of linear and rotor servomotors were realized with Beckhoff TwinCAT® PLC Control.

Figure 1: Laboratory rotating stage. Samples up to 70 kg can be rotated up to a frequency of 1 Hz.

2.2 Description of the Radar Sensor

The used radar device is a newly developed frequency-modulated continuous-wave radar (FM-CW radar) [9]. 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 [10].

Main features of the chosen radar sensor 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. The frequency sweep time for the experiments was chosen such as to achieve 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. 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.. In this study, we have considered the frequency band 24-25.6 GHz (bandwidth B=1600MHz). The I- and Q-channels of the 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 RESULTS

3.1 Detection of Artificial Defects behind a GFR-sample

The realization of the laboratory demonstrator is shown in the left part of Figure 22 with the radar sensor in the foreground. In order to validate the proposed SHM-concept artificial defects have been placed behind the 10mm thick glass fiber reinforced (GFR) sample, i.e. a tool, a corner reflector (to simulate the strong reflections from the lightning conductor), and a water bag. It has been demonstrated elsewhere that the employed electromagnetic radiation is able to penetrate the GFRP-sample in a transmission setup [9]. Hence, we will focus specifically on the differential signal analysis to discriminate different states of the structure.

Therefore, the left column of Figure 22 illustrates a radargram in which the radar signals are plotted when the GFR sample has been rotated from -25° to +25°. From these visualizations a reliable diagnostics is hard to obtain. This can be achieved nicely by means of a differential signal analysis which is well-known e.g. from guided wave-based SHM [11]. Here, the reference measurement is subtracted from the current measurement. The tool as well as the water bag can be accurately determined.

It should be noticed that we have not performed synthetic aperture radar (SAR) signal processing yet. The results presented here are just the proof-of-principle that the objects can be detected. Future work will study the performance enhancement when SAR-techniques will be applied.

Figure 2: (left) Experimental laboratory demonstrator as a model of a wind turbine with radar module at the front; (right) different objects on the back of the 10mm thick GFR-panel (tool, corner reflector, water bag).

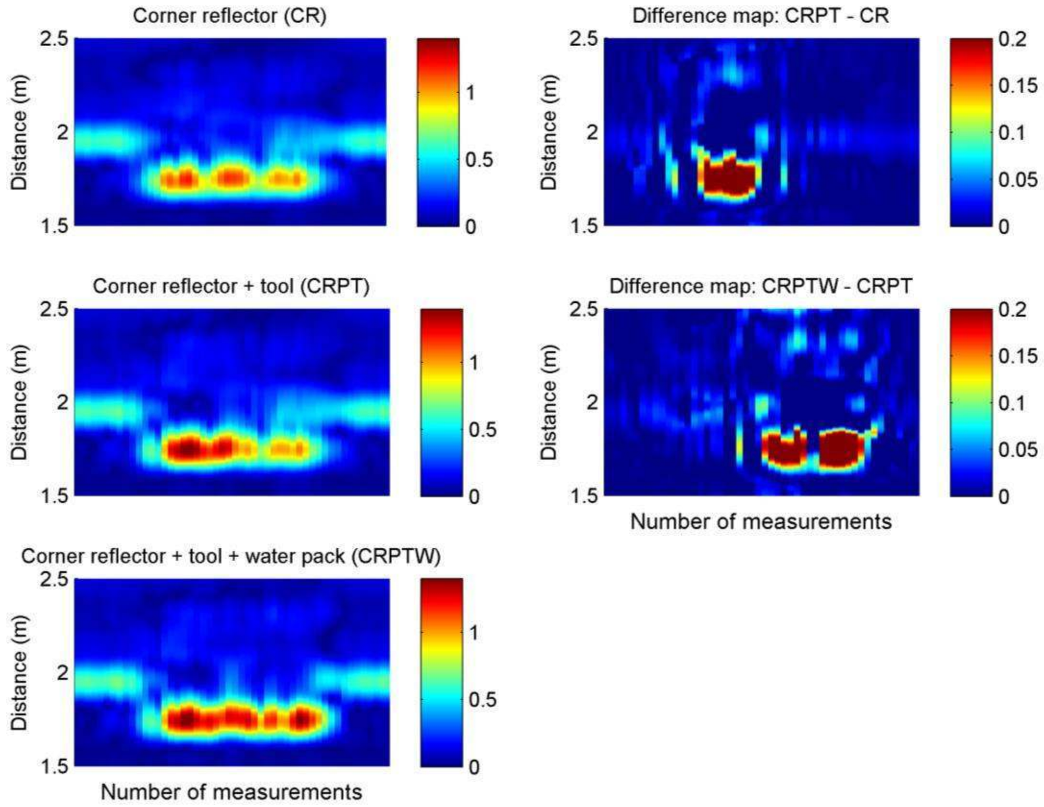

Figure 3: (left) Radargram showing different objects on the back of the GFRP-panel (corner reflector, corner reflector + tool, corner reflector + tools + water); (right) Differential analysis with adapted reference states. The respective local changes are nicely recognizable. The tool can be seen on top and the water bag at the bottom.

3.2 Detection of Surface Pollution

A dirty rotor blade reduces the performance of the wind turbine especially at high wind speeds by about 25 per cent [12]. The main reasons are related to dust accumulation, insect contamination, ice accumulation and surface erosion [13]. Hence, it is of interest for the operator of a wind turbine not only to monitor the health state of the structure (see previous section), but also to monitor the surface state of the rotor blade. Blade cleaning strategies can be triggered, when a dirty rotor blade has been detected [14].

In this section, we have investigated the potential use of radar technology to detect dirt on the surface of the GFR sample from remote distance. Therefore, we have placed a double-sided tape on the GFR sample as shown on the left side of Figure 4 and performed a reference measurement. Next, sugar was poured onto the tape and the second measurement has been recorded.

The result of both measurements is shown in Figure 5 which indicates that the range profiles for the reference state (tape only) and the polluted case (tape with sugar) slightly deviate from each other. A stronger attenuation of the radar signal can be observed in the latter case so that it seems to be possible to identify pollution on the rotor blade. The identification can ben based on the difference in the peak detected amplitude with reference to the background amplitude, which is equal for both measurements.

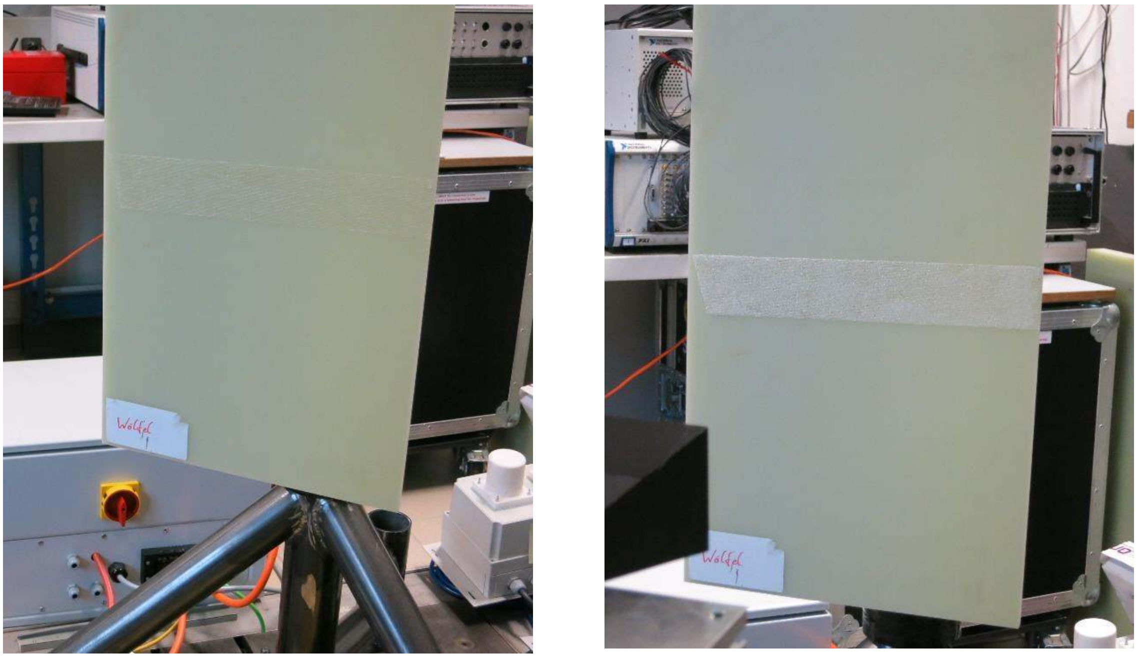

Figure 4: (left) Double-sided tape at the front side of the GFR sample; (right) Double-sided tape with sugar to simulate pollution on the rotor blades.

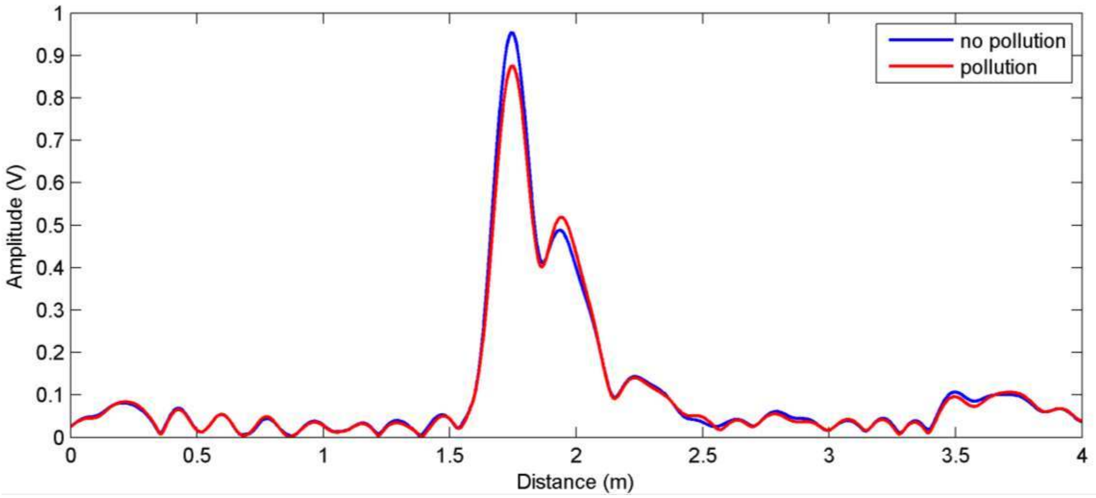

Figure 5: Comparison of a measurement with tape only and the tape with sugar. A stronger attenuation of the radar signal can be observed in the case of sugar on the rotor blade so that it seems to be possible to identify pollution on the rotor blade.

3.3 Analysis of the temperature stability of the radar device

In SHM-applications it is required to consider varying environmental and operational conditions to increase diagnostic sensitivity. We have performed an over-night measurement to study the effect of temperature variations on the range profiles. The results of this basic study are shown in Figure 6. Every 10 minutes a series of 100 measurements have been recorded and averaged. This leads to a total number of 82 measurements that are presented on top of Figure 6. The amplitude changes of the radar sensor are shown at the bottom of the same figure. It can be seen that a continuous amplitude variation occurs that is primarily related to temperature effects. The impact of temperature variations on the range profiles may lead to temperature compensation strategies that are well-established in guided wave based SHM-systems [16].

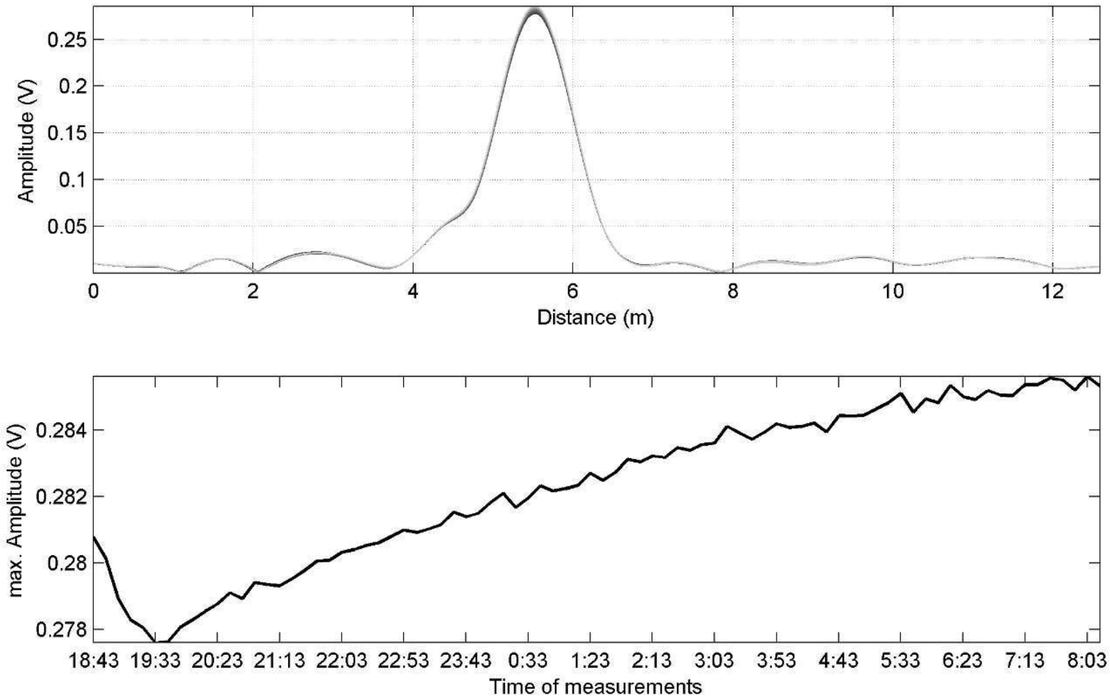

Figure 6: (top) All 82 range profiles form the overnight testing; (bottom) variation of the maximum values.

4 CONCLUSIONS

This paper introduced a laboratory demonstrator system for radar-based structural health monitoring of wind turbine blades. It was shown that different objects can be identified from remote distance successfully. Moreover, we showed the detectability of surface changes related to dirt as well as the influence of temperature on the range profiles which may lead in the future to compensation strategies of the temperature effect.

Future work will focus on the detectability of real damages as well as on the detailed analysis of environmental and operation changes such as temperature variations.

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