Analysis of Changing Environmental and Operational Conditions in a Radar-Based SHM-System for Wind Turbine Blades

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Abstract

Wideband radar sensors are a novel modality for structural health monitoring (SHM) of wind turbine blades. The proposed methodology makes use of a multistatic FMCW radar sensor in the frequency band from 34 GHz to 36 GHz that is installed at a 2 MW wind energy plant (WEP) about 95 m above ground. Inspection of the rotor blade takes place when the blade passes the radar sensor in 6 o’clock position. The antenna array has a Y-shaped design with one radar transmitter (Tx) in the center and three radar receivers (Rx) on each leg. In addition, a blade-ID sensor has been installed in the nacelle of the turbine to identify which blade is currently being inspected.

Besides the general concept of the radar-based SHM system, including data acquisition and real-time signal pre-processing, we will present radar-based imaging results of rotor blades based on the $\omega-k$ imaging algorithm, often used in inverse synthetic aperture radar applications. The latter exploits the rotation of the rotor blades for improved image reconstruction. A special focus will be on changing environmental and operational conditions (EOC) such as wind speed, azimuth, pitch angle, temperature etc. It is demonstrated that changing EOC have an impact on the image reconstruction.

1. Introduction

Radar imaging is applied in many different fields where information regarding hidden objects are required. This can be for example in the fields of security scanning to identify hidden threats [1], biomedical microwave imaging to detect cancer [2] or in the field of ground penetrating radar for the detection of land mines [3]. In this paper, we exploit the capability of microwave and millimetre-wave radiation to penetrate dielectric objects for non-destructive identification of defects in the rotor blades of an operational wind energy plant.

We contribute to the recent developments in the area of condition monitoring (CM) and structural health monitoring (SHM) systems for components of wind energy plants [4], [5]. Following the successful proof of damage detection [6] and localization [7] in laboratory conditions, we present here the installation of the sensor system at the tower of a 2MW wind energy plant at 95m above ground.
2. $\omega$-k image reconstruction algorithm

The $\omega$-k imaging algorithm is widely used in synthetic aperture radar applications to detect and locate an object from the radar data gathered over a two-dimensional aperture [8]–[10]. The $\omega$-k algorithm is an imaging algorithm that uses the FFT-algorithm in the frequency-wavenumber domain. Let $\Phi(x; y; z; t)$ be a wavefield at a point $(x; y; z)$ and time $t$. According to the Fourier theorem in terms of $x$, $y$, and $t$ the wavefield can be expressed as $\varphi(k_x; k_y; z; \omega)$ with the angular frequency $\omega$ and both the wavenumbers $k_x$ and $k_y$ in $x$- and $y$-direction. For the sake of clarity, let $x$ and $y$ be the cross-range dimensions of the synthetic aperture and $z$ be the range dimension in propagation direction towards the target. This wavefield satisfies the Helmholtz equation

$$\nabla^2 \varphi + k_0^2 \varphi = 0 \quad (1)$$

Among the large number of solutions to the Helmholtz equation the most trivial approach is the one of a constant amplitude monochromatic plane wave. Without any loss of generality, the propagation direction can be set as the positive $z$-direction resulting in

$$\frac{\partial^2 \varphi}{\partial z^2} + k_z^2 \varphi = 0 \quad (2)$$

with $k_0 = \omega/c$. Here, $c$ is the speed of light and $k_z = \sqrt{k_0^2 - k_x^2 - k_y^2}$ is the wavenumber in $z$-dimension.

The derivation of the $\omega$-k algorithm is based on the exploding reflector model (ERM), i.e. in case of the mono-static radar configuration the wavefield starts to propagate at time zero with half of the actual propagation distance assuming the radar targets to be the source of the electromagnetic waves. Hence, the received B-scans can be formulated as $\Phi(x; y; 0; t)$ which equals a boundary condition to resolve for $\Phi(x; y; z; 0)$. According to the ERM model, $\Phi(x; y; z; 0)$ equals the wavefield starting at the target and resembles the radar image at once. Under these assumptions, the algorithm can be formulated as

$$\Phi(x, y, z, 0) = \int \varphi(k_x, k_y, 0, \omega) e^{i(k_x x + k_y y + k_z z)} dk_x dk_y dk_z \quad (3)$$

The angular frequency variable is directly related with the wavenumber and can be expressed as

$$\omega = c \cdot \text{sign}(k_z) \sqrt{k_x^2 + k_y^2 + k_z^2} \quad (4)$$

and
\[ dw = \frac{c \cdot k_z}{\sqrt{k_x^2 + k_y^2 + k_z^2}} dk_z \]  

which provides a variable transformation in Eq. (6) that can be written as

\[ \Phi(x, y, z, 0) = \int \frac{e^{ik_z}}{\sqrt{k_x^2 + k_y^2 + k_z^2}} \delta(k_x x + k_y y + k_z z) dk_x dk_y dk_z \]  

where the first term of the integrand is the Jacobian determinant generated by the variable transformation. Note here, the last exponential term has the expression of an inverse FFT kernel. However, the application of Fourier operations imply equidistant and equifrequent sampling, respectively. Actually, for a linear or planar antenna track the wavenumber domain data is equifrequent except for \( k_z \). In order to prepare the data for the inverse 3D-FFT the data must be resampled in the frequency domain, which is known as the Stolt interpolation. Finally, the radar image can be obtained by the application of an inverse FFT in terms of \( k_x, k_y \) and \( k_z \).

### 3. Radar sensor installation at a 2 MW wind turbine

Figure 1 shows the installation of the radar sensor at the tower of a 2 MW wind energy plant about 95m above ground. The radar module consists of a transmitting antenna in the centre of the module and 9 receivers, with three receivers on each leg. This configuration shows optimum array imaging performance as shown by simulations in [11]. The frequency band of the radar system ranges from 34GHz to 36GHz with an output amplitude of 30 dBm and horn antennas with a gain of 24 dBi. The sweep time of the frequency-modulated continuous wave (FMCW) radar is approximately 400µs.

![Figure 1. Photo of the radar sensor installed at a 2 MW wind turbine about 95m above ground.](image-url)
Figure 2 illustrates a system overview with multiple sensors outside the wind energy plant (WEP) and several components inside the WEP tower. Key components for the SHM system is the 35GHz radar array and a temperature sensor inside the radome to measure the current radome temperature. The raw data are forwarded to a multichannel A/D-converter X3-2M from Innovative Integration (Camarillo, USA). This device enables a continuous streaming of measurement data to the PC at a high sampling rate of 5 MSPS. By means of simultaneous sampling, a synchronization of the sensor signals can be achieved. The system also interfaces the WEP control to read the current WEP parameters during a measurement. Moreover, a blade-ID sensor in form of a reed contact has been installed in the hub to provide information which one of the three blades has been inspected. Finally, the measurement PC has an internet connection to enable remote access.

The smart cameras and the ultrasound microphone are used for simultaneously investigation of bat activity close to the WEP [12], and will not be further considered in this article.

![System overview, after [9].](image)

### 3. Analysis of changing environmental and operational conditions

#### 3.1 Turbine parameter fluctuations over 24 hours measurement campaign

A total number of 395 datasets have been recorded over a 24 hours measurement interval. The fluctuations of the turbine parameters are illustrated in Figure 3. It can be observed that a significant change in the wind turbine parameters can be identified. Those variations have to be considered in a radar-based SHM system for wind turbine blades.
A different representation of the wind turbine parameters is shown in Figure 4, where the power is plotted versus the azimuth angle of the nacelle. For comparison, the azimuth angle of the radome installation is at approximately 220°. At this angular position the radar illuminates the rotating blades in an orthogonal way.

Three datasets are highlighted in Figure 4 that are named as datasets A, B and C. Those will be investigated in more detail in Section 3.2. Datasets A and B have the same angular position, but a different associated power. Dataset C has a different azimuth angle and the power is comparable to the other two cases. Table 1 summarizes the wind turbine parameters for these datasets.
### 3.2 Image reconstruction at different wind turbine parameters

In this section the $\omega-k$ imaging algorithm is used for image reconstruction. Therefore, the three datasets described in the previous section are considered. The first row of Figure 5 shows a radargram (or waterfall) diagram of subsequent radar measurements, where the horizontal axis represents the number of measurements and the vertical axis the distance between a passing rotor blade and the radar sensor. In each case, receiver channel #1 is studied. It can be observed that small differences can be observed between the radargrams of datasets A and B. On the other hand, strong differences occur for the radargram of dataset C. From the radargram figures the front and back wall echo can be seen, showing that a full blade penetration is possible.

Given by the fluctuations in the radargram (even for datasets A and B), it might be more robust to perform an image reconstruction and perform the damage detection on the image rather than the raw signals. Therefore, the bottom row of Figure 5 illustrates the image reconstruction result of the rotor blade for the three cases. Again, the results for datasets A and B are very similar. On the other hand, a big difference occurs for the dataset C. This suggests that the azimuth angle has a significant influence of the image reconstruction results, whereas the bending of the blades, correlated to the power, has a minor effect. A radar-based SHM system must account for these variations in azimuth by establishing multiple baseline measurements.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Azimuth (°)</th>
<th>Power (kW)</th>
<th>Wind speed (m/s)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dataset A</td>
<td>213.6</td>
<td>438.1</td>
<td>6.4</td>
<td>16.0</td>
</tr>
<tr>
<td>Dataset B</td>
<td>213.6</td>
<td>366.2</td>
<td>5.9</td>
<td>16.0</td>
</tr>
<tr>
<td>Dataset C</td>
<td>232.9</td>
<td>385.6</td>
<td>6.0</td>
<td>12.0</td>
</tr>
</tbody>
</table>

Figure 5. (top row) radargram for datasets A, B and C (bottom row) image reconstruction result for the three datasets
Next, the differential radar images have been computed that are shown in Figure 6. It can be observed that the image difference between datasets A and B is rather small. Significant differences can be seen for the case of the differential image between datasets A and C. This result again underlines the significant effect of the azimuth position and reduced effect of the loading of the wind energy plant.

The images shown in Figure 6 can be used in the future for the definition of a damage index, e.g. as the sum of the pixel values of the difference image. Such an approach would be similar to those used e.g. in guided wave-based SHM systems where the differential signal between a baseline and the current measurement is widely used as the basis for a damage indicator definition [13]. Future research will show the performance of this approach.

![Figure 6. (left) normalized differential image between dataset A and B, (right) normalized differential image between datasets A and C.](image)

4. Conclusions

This paper presented a radar-based imaging approach for the inspection of rotor blades of an operational wind energy plant. The well-known $\omega$-$k$ imaging algorithm has been applied to radar measurements obtained from a field installation. It was found that changes in the azimuth angle had significant influence on the image reconstruction result, while changes in the wind loading has a minor effect. It was demonstrated here, that a differential imaging approach might be suitable for the definition of a meaningful damage indicator. The performance of this approach has to be tested in future research.

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References


