A Novel Mechanical Stress Measurement Method Applied to Wind Turbine Rotor Blades

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Abstract: Rotor blades for wind turbines are made of glass-fibre reinforced compound material (GFRP). Their size in off-shore wind farms exceeds 50m in length and 15t in weight and their speed exceeds 300 km/hour. They have to be designed to withstand wind and weather over their approximately 20 years of lifetime. The ability to monitor the mechanical stress is crucial in order to reduce maintenance costs and to maximize operational availability. This paper presents a combined simulation model of SPICE and COMSOL for a novel mechanical stress measurement method applied to wind turbine rotor blades. The combination between COMSOL and SPICE helps to reduce the computation time. This allows to focus on design details with COMSOL while modeling the overall design using SPICE. The proposed measurement method based on transverse electromagnetic (TEM) Waveguides is outlined. The workflow of setting up the combined SPICE/COMSOL-model is described in detail. Measurements and simulation results are compared. Figure 1 shows the forces on the wind turbines rotor blade [1], [2], [4].

Keywords: Rotor blades, mechanical stress, Combination between COMSOL & SPICE, TEM-Waveguides.

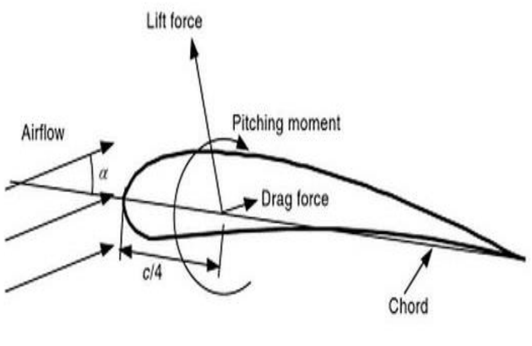

Figure 1) Forces and moments on an airfoil section [1]

1. Introduction

This work is included into the research project *High-Performance Fiber-Composite Rotor Blades for Wind Turbines through Plasma-Treatment*. Which is founded by the Arbeitsgruppe und Geschäftsstelle Innovative Projekte (AGIP)[1]. The aim of this subproject is to develop alternative strain measurement methods for online monitoring of mechanical stress imposed upon rotor blades. Strain sensors have to be compatible with the glass-fiber compound and its production process [5].

The importance of the rotor blade condition monitoring (RBCM) system is growing. There are several measurement systems based on different technologies. The hereby presented RBCM is based on the frequency domain reflectometry technique (FDR). The FDR method will be discussed in details in theory section. The proposed mechanical strain measurement method is applicable to existing rotor blade production units. This makes it easy to adopt it to the production. The simulation model discussed in this paper relies on the combined power of COMSOL and SPICE. According to simulation and measurements it is now possible to monitor the strain of rotor blades permanently. Therefor only a few modifications on conventional rotor blades are necessary. In the model shown in this paper the rotor blade is finite element method (FEM) modeled by its physical properties and geometry using the COMSOL RF-module. All other components included in the hardware that detects the mechanical stress of the rotor blade are described in SPICE. SPICE models the circuit elements which need not to be described by their geometry. The SPICE models are imported into COMSOL using the AC/DC-module. The circuit behavior is computed in the frequency domain. A complete 3-D COMSOL model is necessary in order to describe the geometry of the rotor blade. The use of global parameters describing the geometry eases design optimization in the future [3] [4].

[1] For more details about AGIP: http://agip.fh-hannover.de/245.html

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2. Theory

2.1 Reflectometry

Reflectometry measurements can be used for many applications. One of the common applications is locating electrical wire faults. Assuming that an electrical wire is integrated into the GFRP structure of the rotor blade reflectometry measurements can adopted to measure their mechanical stress. There are several methods of reflectometry measurements as time domain reflectometry (TDR), Frequency domain reflectometry (FDR), Spread spectrum time domain reflectometry (SSTDR), and optical frequency domain reflectometry (OFDR). The reflectometry methods depend on the signal propagation along the waveguide. The wire fault can be determined through the reflection information e.g. delay received back from the wire. The reflection coefficient can be given by the equations below [4], [5] - [7].

$$\Gamma = \frac{Z_0 - Z_L}{Z_0 + Z_L}$$

Where Γ is the reflection coefficient Z_0 is the characteristic impedance (for in instrumentation $Z_0 = 50\Omega$). Z_L is the impedance towards the load. Figure 2 shows the circuit location of Z_L and Z_0.

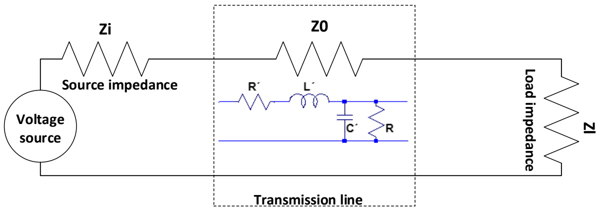


Figure 2) Location of Z_0 and Z_L

The TDR uses a rectangular pulse signal which is fed into a twisted pair wire. The TDR measures the response of the system in the time domain (voltage versus time) to a given excitation. The excitation can be realized through a unit step function [4]-[8]. The location of the wire disorder can be detected through the signal propagation time. In order to detect a high resolution change in length by TDR. A high time resolution T must be realized.

For example a sample of $l = 10m$ length with a propagation velocity $v = 15\,\frac{cm}{ns}, \varepsilon_r = 4$ demands for $T = 5$ps.

$$T = \frac{2.(l.1\%)}{v.2^N} = 5ps$$

T in case an N=8 bit resolution is to be achieved at 1% elongation not feasible inexpensive. The rise time of the pulse and the sampling rate of the detector determines the accuracy of the TDR method. Compared to the TDR method FDR is less sensitive to noise due to the better algorithms in the frequency domain (FD).

An FDR based measurement system with a known defect is on the other hand easy to implement. The simplest way to realize the defect is a short cut. A twisted, short circuited two wire cable (twisted-pair) made out of enameled wire has a typical characteristic impedance of $Z_0 = 50\Omega$. The FDR has an improvement in signal noise due to the easy adoption of the noise reduction algorithms. The FDR method enables a clearly display of the frequency depended characteristics as the needed sweep frequencies includes only the frequency ranges chosen by the operator. One of the disadvantages of the FDR technique is that the propagation velocity determines the accuracy of the measurement. The propagation velocity should be determined in advance. The propagation velocity of GFRP is well known [4]-[7]. Due to the mentioned advantages and disadvantages of FDR and TDR we are convinced that the FDR technique is the most suitable method for our intended application.

2.2 Frequency domain reflectometry (FDR).

The shown mechanical stress measurement system is based on the FDR technique. It feeds a swept radio frequency (RF) sine wave into a twisted pair short circuited copper[2] wire. The signal sweeps travel to the end of the wire (to the short circuit) and travel back after reflection to the signal source. The reflected sine wave can be examined in terms of three different properties.

[2] $Diameter\ \emptyset = 0.315\ mm$

These properties (Phase, magnitude and frequency) enables three different FDR measurement possibilities.

The different FDR techniques can be adapted to detect faults in the wind turbines rotor blades [4]-[7].

1. Frequency Modulated Carrier Wave (FMCW).
2. Phase Detection Frequency Domain Reflectometry (PD-FDR).
3. Standing Wave Ratio (SWR).

The different FDR measurement options will not be discussed in this paper. The second and the third method are the applied method [4]-[7].

The applied FDR method uses the property of the TEM waveguide that each change of the geometry of the material of the rotor blade causes a reflection of a part of the energy of the Waveguide. A custom made PLL frequency generator generates a sin wave which is stepped over a specific bandwidth using two discrete frequencies with a frequency step size Δf. The frequencies are f_1 and f_2 and a center frequency f_0 . A detection hardware detects the reflected signals. In case of a mechanical stress the transmission line will be lengthened by Δx. The voltage at $f_1 \downarrow$, and the voltage at $f_2 \uparrow$. The voltage difference $\Delta U = U(f_2) - U(f_1) \uparrow$. This voltage increment enables the detection of the stress applied to wind turbines rotor blades [4]-[7].

Figure 3-a shows a block diagram the applied FDR technique. Figure 3-b shows the SPICE model of the block diagram.

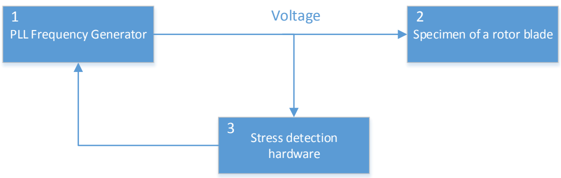
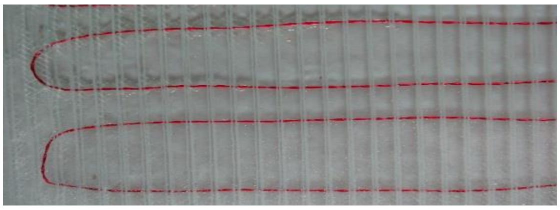


Figure 3-a) Block diagram of FDR technique

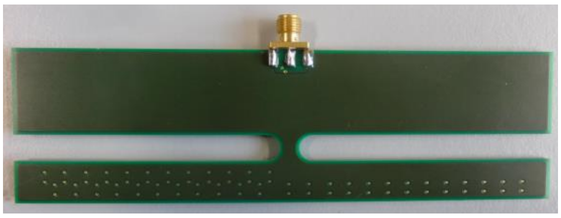
2.3 Test setup

The components of the block diagram figure 3-a will be described in this section.

Block 1 shows the phase locked loop (PLL) based two channels frequency generator. Block 2 describes a custom made model of a rotor blade with a 50Ω matching impedance and an integrated twisted pair copper wire which allows the application of the method described in section 2.2. The specimens material consists of glass-fibre reinforced plastic (GFRP). Figure 4-a and 4-b show two different versions the Specimen. The sample 4-a has been prepared in our laboratories. The sample 4-b uses a standard 4 layer printed circuited board (PCB) with an integrated 50Ω strip line with $l = 1.5\ m$.



(a)



(b)

Figure 4-a) GFRP version of the specimen, Figure 4-b) PCB version of the specimen

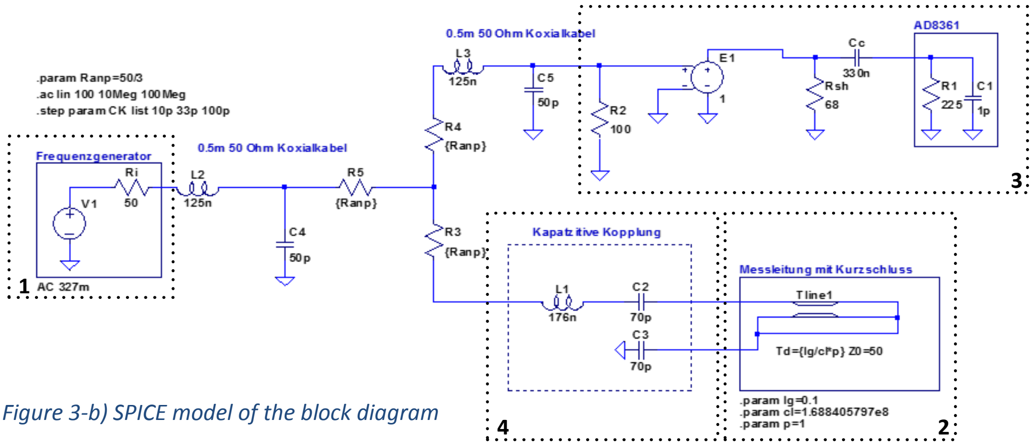


Figure 3-b) SPICE model of the block diagram

Figure 5 shows the test setup with custom made hardware.

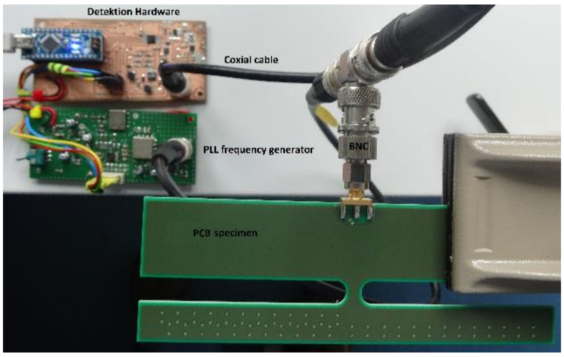


Figure 5) Test setup with custom made components

Figure 6 shows the test setup. The PCB specimen has been tested under different tensile loads varieties F= 0…2000 N.

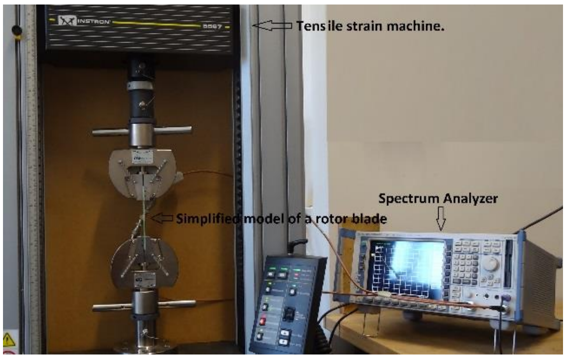


Figure 6) Test setup

The spectrum analyzer captures the frequency dependent voltage which is crucial for the detection of the mechanical stress of the specimen. Figure 3-a shows the block diagram of the test setup. All units are connected to each other through a 50Ω coaxial cable.

A non-direct conduction path between the detection hardware and the rotor blade is necessary to save any component from damages which could be caused e.g. through a lighter stroke. The galvanic isolation has been realized in the SPICE simulation model shown in Figure 3-b in block 4 as a capacitive coupling. The needed capacitance can be calculated through modulation with a COMSOL/SPICE software.

3 The COMSOL model

The here shown simulation model uses COMSOL[3] multiphysics ability to combine different physical modules together. The GFRP rotor blade with the integrated twisted pair cupper wire is FEM- modeled by its physical properties and geometry using the COMSOL RF-module and electromagnetic wave (emw) as a modelling function. Figure 7 shows a section of the 3D COMSOL model which describes the rotor blade and the twisted pair wire. The real simulated length is 100 mm.

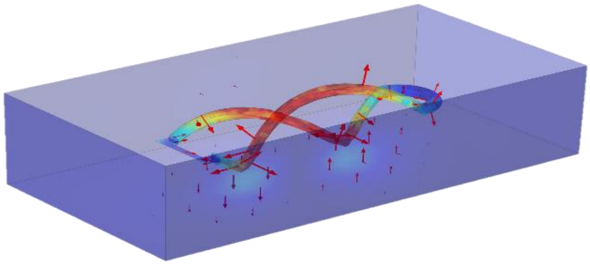


Figure 7) Section of the 3D COMSOL model

The other components which are necessary to detect the stress detection hardware is described in SPICE. The SPICE model is connected to the COMSOL model through the AC/DC module and the electrical circuit (cir) modelling function. Figure 3-b shows the SPICE model which contains the frequency sweep PLL generator, the detection hardware and the capacitive coupling.

The model separation between COMSOL and SPICE reduces the computation time. The use of global parameters describing the geometry eases design optimization in the future. The circuit behavior is computed in the frequency domain through the frequency domain as study in COMSOL. The used COMSOL solver is MUMPS it is fast in computation, multi-core and cluster capable.

4 Results

In this section we present the various simulation and experimental results, which we obtained from the simulation models or from the experimental test setup. Figure 8 shows a SPICE simulation of the waveguide varieties of the specific line resistance as depicted in figure 2 with R`= $1m, 1, 2 \ and \ 5 \ \frac{\Omega}{m}$. R`= $\frac{5\Omega}{m}$ matches the measurement in Figure. 11 best.

[3] 4.3 is the used COMSOL version.

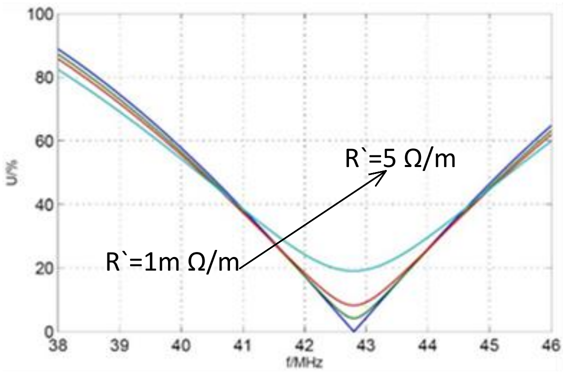


Figure 8) Waveguide simulation

Figure 9 shows the simulation of the frequency versus voltage diagram. The normalized voltage is shown in percent. The diagram shows the two frequencies f_1, f_2 which are explained in section 2.2 and a frequency step Δf of 4MHz. The wire is lengthened in the ramp of $\frac{\Delta x}{l} = 0 \ldots 2\%$.

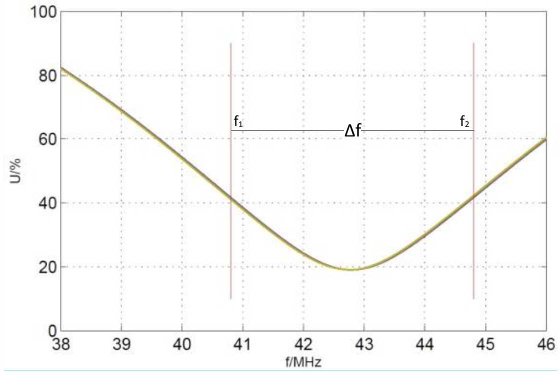


Figure 9) Voltage versus frequency diagram

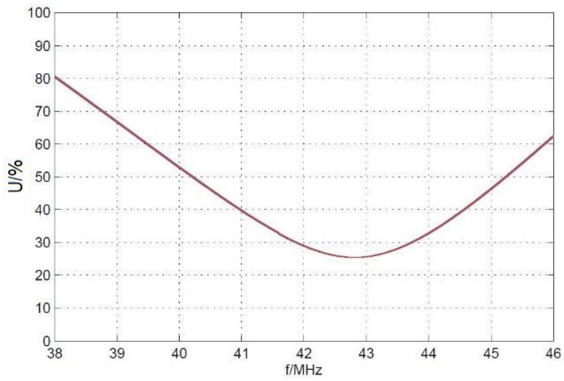


Figure 10) Experimental result of the test setup

The measurement shown in Figure 10 depicts the experimental measurement results which can be directly compared to the simulation result shown in figure 9. Such a diagram can be captured through the custom made detection hardware shown in figure 5 or through the spectrum analyzer shown in figure 6. The voltage difference cannot be captured directly through the spectrum analyzer. The captured raw data must be analyzed by software.

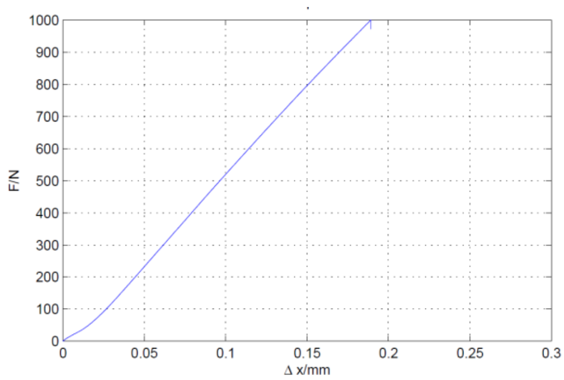


Figure 11) Elongation versus force diagram of the PCB specimen

Figure 11 shows the elongation Δx versus force F diagram of the PCB specimen. This diagram is generated during the test setup from the tensile strain shown in figure 6.

Figure 12 shows that the voltage ΔU=U(f_2) - U(f_1) correlates to the displacement Δx caused by the tensile stress applied to the PCB specimen.

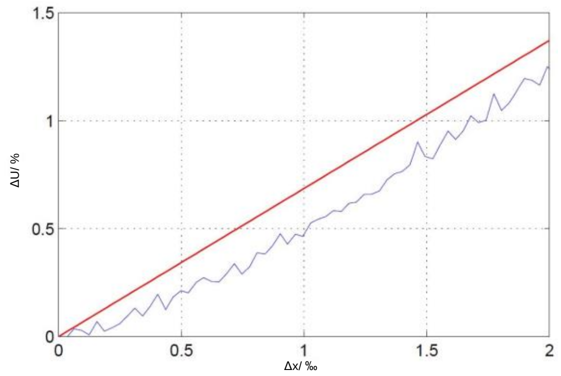


Figure 12) A comparison between the simulated (red) and the measured (blue) Δx versus ΔU diagram

The measurements shown in figure 11-12 were carried out several times to ensure the reproducibility of the applied FDR method.

5 Conclusion

This paper demonstrates a FDR based novel mechanical stress measurement method applied to wind turbine rotor blades. It is a new generation of rotor blade condition monitoring (RBCM) system. Here, we applied a 3-D finite elements frequency domain method FEM linked to a SPICE circuit to simulate the stress monitoring sensor. Compared to empirical methods, the shown method offers a suitable performance for the design and the conception of RBCM systems, for monitoring the mechanical stress applied to rotor blades during its whole lifetime. By this approach we were able to integrate a twisted pair copper wire to the glass-fibre reinforced compound material (GFRP) in order to use it for measurement purposes.

In this paper, we have investigated the simulation of a novel mechanical stress measurement method applied to wind turbine rotor blades. The simulation results and the results from the empirical measures can provide useful information and empirical data about this novel RBCM method.

6 References

[1] (2010). In J. G. James F. Manwell, Wind Energy Explained: Theory, Design and Application 2nd ed. (S. 103). United Kingdom: Wiley.

[2] Hau, E. (2008). Windkraftanlagen-Grundlagen,Technik, Einsatz, Wirtschaflichkeit vierte Auflage. Germany: Springer.

[3] Hegab, A. H. (2013). Untersuchung einer kapazitiven Kopplung mittels COMSOL Multiphysics zur galvanisch getrennten Messung von Materialausdehnung in Windkraftanlagen. Goettingen: HAWK Masterprojektarbeit (unveroeffentlicht).

[4] Inc., P. e. (2004). Broadband Services, Applications, and Networks: Enabling Technologies and Business Models. USA: IEC publications pages 560-570.

[5] Kaerst, J. P. (2010). Entwicklung alternativer Messverfahren zur integralen Dehnungsmessung in ausgedehnten Strukturen. Goettingen: HAWK Forschungsbericht (unveroeffentlicht).

[6] Mukhopadhyay, S. C. (2011). New Developments in Sensing Technology for Structural Health Monitoring. New Zealand: Springer, Pages 161-175.

[7] Sharma, C. R. (2009). Low power CMOS sensor for detecting faults in aircraft wiring . University of Utah (Page 11).

[8] Thumm, M. (1998). Hochfrequenzmeßtechnik. Stuttgart: Teubner.