WIRELESS DAMAGE MONITORING SYSTEM BASED ON RFID

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Abstract
Radio-frequency identification (RFID), a technology for transmitter-receiver systems in order to automatically and contactlessly identify and locate objects using electromagnetic fields or waves, is a versatile technology for wireless power and data transmission. A new approach for RFID has been investigated to detect mircocracks and failure of preform overlappings for fiber reinforced materials.
The antenna coil and the capacitor of the RFID device investigated form a resonance circuit in the frequency range of 122 kHz. A carbon fiber sensor (CFS) having a specific resistance and inductance can be integrated for damage detection. Due to the damage the resonance frequency of the circuit is shifted, which can be detected wirelessly by the transmitter device. Since the CFS measures along its length, the shape of the sensor element can be adapted to specific monitoring problems. Advanced textile techniques, like crocheting technique, has the potential to keep the costs low also for complex shaped CFS-patches. The behavior of the resonant circuit was measured and verified by means of a LTspice IV simulation. The results show that the low-cost and adaptive RFID-system is predestined to monitor the durability of the bondline of different structural elements and can help with early detection of overstressed and damaged zones.

1. Introduction

It has been shown that carbon fibers can be applied as piezoresistive sensors to measure strains and microcracks of CFRP-structures [1-7]. The ex-PAN fiber T300B was identified as one suitable fiber for a carbon fiber sensor (CFS) because of the excellent linear piezoresistive behavior up to a strain level of 0.6%. The CFS consists of a single carbon fiber roving (1k) with electrical connected endings embedded in a sensor carrier (i.e. GFRP-patch) for electrical insulation. Several CFS can be applied to form a sensor mesh to measure structural deformations or to detect damages in composite structures, like pressure vessels. The CFS-technology has been combined with radio-frequency identification (RFID) to get a wireless damage monitoring system.
RFID, a technology for transmitter-receiver systems in order to automatically and contactlessly identify and locate objects by using electromagnetic fields, is an established technology in many industrial fields. In [8] a concept study regarding the feasibility of the implementation of the radio frequency technology into carbon fiber material was investigated. Technical approaches and methods have been developed to achieve this implementation regarding material compatibility. Referring to the applications (identification and monitoring) an operating frequency in the range of 150 kHz (low frequency) for a close-coupling system (distance up to 3 cm) was defined [9,10]. Identical antenna coils made out of different materials (carbon fibers, nickel coated carbon fibers and copper) were manufactured and investigated. The characteristic values, like resistance and inductance, were determined and the reduction of the inductance of the coils were measured when placed on CFRP as background material. In addition to the CFRP-coils a structural CRFP-based double-layer capacitor

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was designed with carbon fiber electrodes and lithium ions as charge carrier. The use of carbon fibers for the manufacturing of the transponder coil and of a CFRP-capacitor seems very promising in the field of RFID. By coupling the secondary resonant circuit to a primary resonant circuit with an inductance of 297 μH and an applied voltage of 8 V an effective power between 4.6 mW and 170 mW could be noted due to a resonant peak.
Concerning this paper a RFID based damage monitoring device was investigated for CFS sensor meshes having the following aspects:

- wireless
- no electrical energy required for the receiver device integrated in the CFRP-structure
- application of robust and basic electrical components (coil and capacitor)
- even poorly accessible areas of a construction can in principle be easily monitored
- system can be integrated or covered beneath a coating to prevent environmental effects

Due to the simplicity of the design, the RFID based damage detection system can be an alternative to other approaches based on microprocessor controlled intelligent sensor meshes for many applications.

2.1 RFID based damage detection system

A RFID system is typically made up of two components: the transponder or tag and the data acquisition device often referred to as reader or transceiver [9, 10]. The tag is generally physically attached to an object or integrated into the product. Inductive coupling is used at low frequency RFID systems operating in the near field. Therefore, the reader transmits energy to the passive tag at frequencies between 125 - 135 kHz. Concerning this paper a simple receiver device without semiconductor chip, according to the requirements by the implementation in CFRP, was designed and investigated. The combination of antennas, capacitors and CFS form a resonant circuit. The shape and position of the CFS can be adapted to a specific monitoring problem. The structural damage should have a strong effect on the specific electrical properties of the receiver device, which can be detected wirelessly by the transmitter device.
Two configurations were investigated. The first concept (configuration A) provides that the receiver side of the RFID based damage detection device consists of a coil and a capacitor only. This represents the minimum configuration necessary for RFID. The antenna coil is placed at the location to be monitored, which can be i.e. the bond line between two parts or a preform overlapping. If a damage occurs, the coil will be affected or even destroyed. The characteristic values of the resonance circuit will change in such a way that it can be detected by the transmitter. Considering this concept it become quite obvious that the antenna coil should exhibit brittle material behaviour.

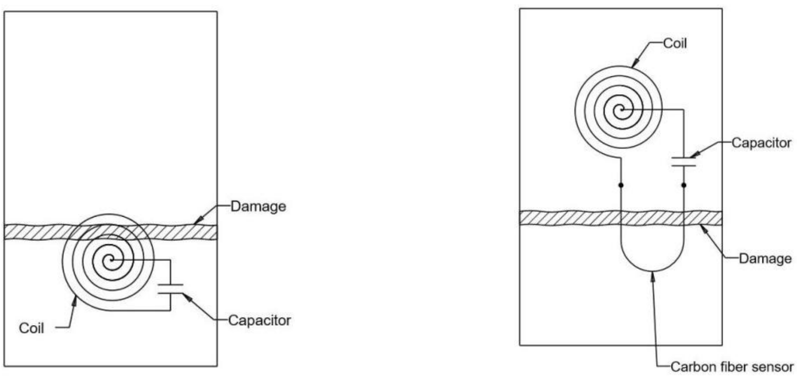

Figure 1. Schematic description of configurations investigated (configuration A left, B right).

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In this case also small damages should have a stronger influence on the characteristic values of the resonance circuit compared to an antenna coil having tough or plastic properties. Therefore carbon fibers or nickel coated carbon fibers are preferred materials for the antenna coils of configuration A.
For the second concept (configuration B) the RFID device is extended by a CFS. In this case the CFS is shaped and positioned in such a way that it can monitor the critical location. If damage occurs the CFS is affected or destroyed. Considering this concept, the antenna coil can be made out of copper, which allows a higher energy transmission compared a CFRP-coil [9]. A schematic description of the two concepts is given in Fig. 1.
This paper considers the detection of microcracks and the detection of a failure in preform overlappings. Concerning the detection of mircocracks glass and carbon fiber reinforced laminates (GFRP, CFRP) were applied having a lay-up $[90_4,0]_{sym}$. Since microcracks will appear in the 90° layers at strain levels higher than 4,000 µm/m, the influence of damage to the laminate on the sensor signal can be analyzed. In this case an elliptical coil was applied to increase the effect of the mircocracks on the coil (Figure 2a). Figure 2 b, c shows the configurations A and B to monitor the failure of the preform overlapping, respectively.

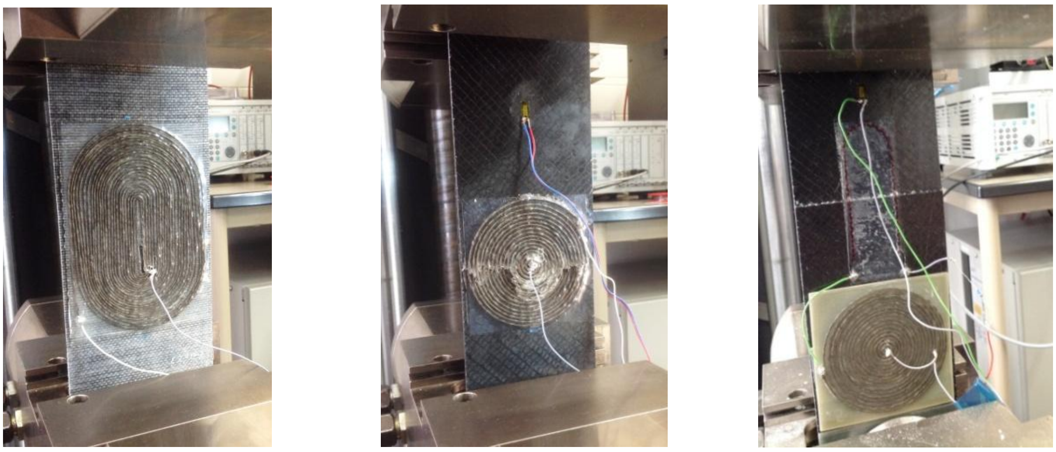

Figure 2 a, b, c. Different configurations to monitor microcracks (left) and the failure of preform overlappings (configuration A in the center and configuration B, right picture)

2.2 Simulation

The behavior of the resonant circuit was measured and verified by means of a LTspice IV simulation. Figure 3 shows the simulation model applied for the configuration B. To simulate the increase of the resistivity in the case of damages, the resistance R2 of the receiver circuit varied from 0 to 10 kΩ. The effect of the resistivity increase on the impedance of the transmitter circuit as well as on the phase angle and the damping of the resonance circuit was determined.

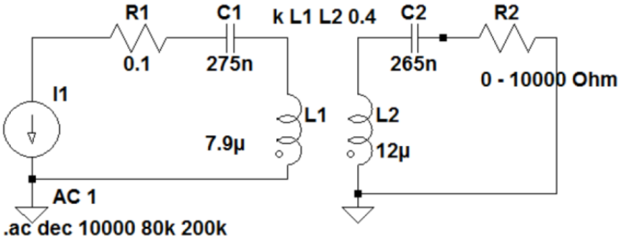

Figure 3. Simulation model for coupling experiment as used in the set-up

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3. Experimental

The nickel coated carbon fiber yarn Tenax HTS 40 A23 12K and the uncoated carbon fiber Toray T300B, 1k were selected as fiber materials for the antenna coils. The uncoated fiber used has only 1,000 filaments compared to the nickel coated carbon fiber, which had 12,000 filaments. To get the same number of filaments and more importantly the same conductor diameter of the coil, the fiber roving was set 12 times, twisted and then inserted into the coil mould. Electrical isolated copper wire (1.0 mm) was applied for the cooper coils. All circular coils had an outside diameter of 82 mm, with 22 turns, distance from turn to turn of 1.0 mm. The dimensions of the elliptical coil was 150*82 mm with 23 turns.

To form the carbon reinforced fiber yarn into the shape of an Archimedean spiral a negative mould was constructed. As a material for this purpose Polytetrafluorethylene (PTFE) was chosen, in order to avoid bonding of the cured material. The roving was impregnated by means of an injection needle with 2.0 ml/m adhesive and then cured at 180° C for 3 hours. The used epoxy resin adhesive (HBM EP310S) has a very low viscosity hence it is able to penetrate the individual filaments of the fiber roving through the capillarity. A vacuum process was applied to bond the coils and the CFS to the specimens using epoxy resin. To avoid a short cut between the coil and the specimen different isolators materials were applied. For configuration A a polyester layer was used, thin enough to avoid a reinforcement of the overlapping. For configuration B a 1mm thick GFRP laminate was selected (Figures 2 b and c).

Automated fiber placement (AFP) and stitching was applied to manufacture the u-shaped CFS to monitor the failure of the preform overlapping. To avoid short circuit between the CFS and the carbon laminate a polyester layer was selected as carrier material. A galvanic process is applied to perform the electrical connection at the endings of the CFS. The CFS can be connected to the coil and capacitor through soldering. Tab. 1 gives an overview of the different configurations tested. Conventional capacitors were selected to get a resonance frequency of around 125 kHz.

Table 1: Overview of the different configurations tested

Damage	**Mircocrack detection**		**Failure of preform overlapping**			
Configuration	A		A		B	
Coil	carbon	nickel/carbon	carbon	nickel/carbon	nickel/carbon	copper
CFS	-		-		carbon	

Reference specimens were used to examine the behavior of the CFRP-coils when they are subjected to high strain levels. In this case the lay-up of the specimen was $[0_4]_{sym}$ to avoid any damage initiation from the laminate.

A non crimped fabric (NCF, 300 gr/m^2) having the lay-up $[+45,-45,0,0]_{sym}$ was used for specimens with the preform overlapping. The length of the overlapping was 50 mm. GFRP and CFRP was applied for the analysis of the mircocrack detection. In this case the laminate was $[90_4,0]_{sym}$. All specimens were cured by means of a vacuum bag. An epoxy resin (L20/EP) was applied using a cure cycle of 10 hours at room temperature and a post-cure cycle at 65°C. The tabs are manufactured separately and bonded to the specimen. A universal testing machine (Zwick 1465) was applied to perform the mechanical tests having a hydraulic clamping device. Strain gauges (HBM: LY 11-10-120) were used to determine the strain level of the specimens. A LCR-meter (Instek 811OG) was used to determine the characteristic RFID-values of the receiver device.

4. Results

For the different concepts investigated the impedance, resistivity, inductance and phaseangle of the receiver device were measured before (reference value) and after the damage occurred. Based on these

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values the influence on the characteristic properties of the RFID approach can be determined. In combination with the simulation tool the behavior of the transmitter can assessed.
Figure 4 shows the results of the reference laminate $[0]_{sym}$. The load was increased in steps up to a load level of 90 kN. After the each load level was reached, the specimen was unloaded and the data was recorded. Up to a load level of 60 kN, which corresponds with a strain level of 0.6%, the magnitude of the shifting is within the assumed measurement spreads. Based on this result it can be assumed, that the measured signals (here inductivity and resistivity) are not influenced by a damage of the coil itself. At higher load level first signal changes can be observed, which can be attributed to a debonding of the coil.
Figures 5 shows the corresponding values for a preform overlapping with a CFS as indicating sensor element (configuration B). If the load is applied smoothly, like it is the case for the testing machine, the failure of the preform overlapping appears in several steps. Concerning this study the load introduction was stopped after the first crack appeared. The failure of the joint has a strong influence on the resistance, the impedance and the phaseangle for both configurations tested. The difference between the reference value and the value after failure is 10 to 40 % depending on the frequency. The data determined for the receiver device allow different options for the transmitter to indicate the damage. Based on the results the development of a RFID based damage detection system seems possible for the monitoring of the preform overlapping or related structural damages, like the debonding of skin-stringer elements.

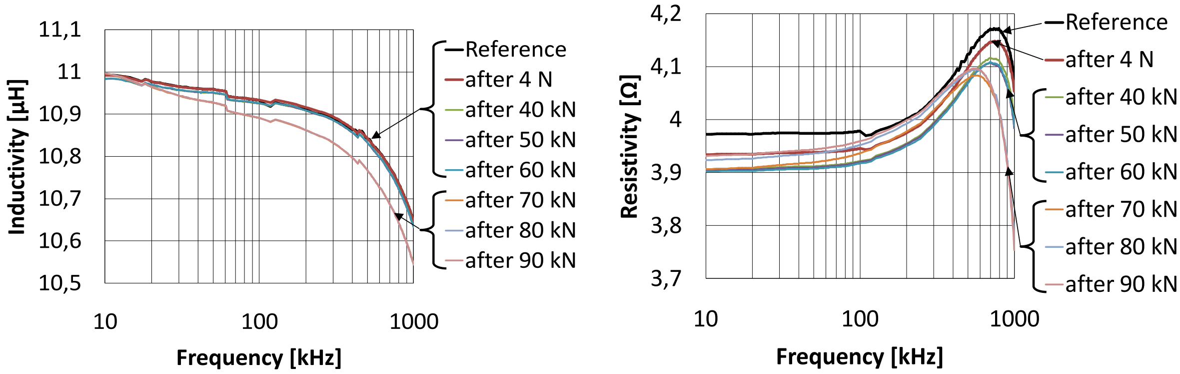

Figure 4 a, b. Inductivity and resistivity of the CFRP-coil as a function of the load level for the reference laminate $[0_4]_{sym}$

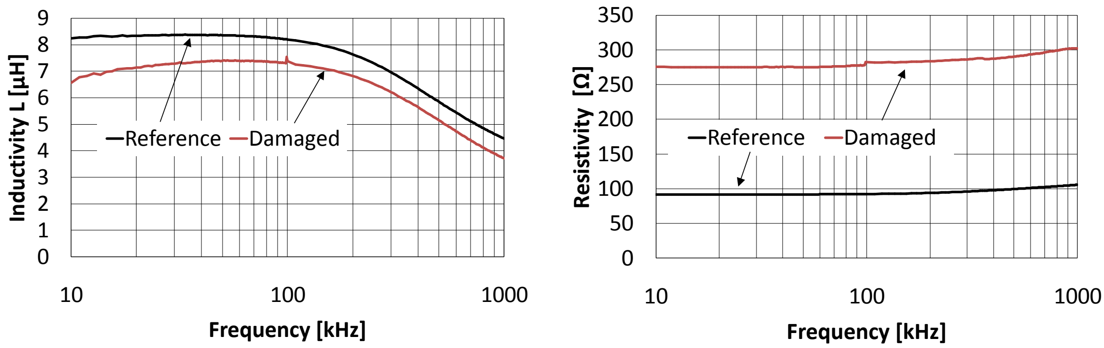

Figure 5 a, b. Inductivity and resistivity of the coil to monitor failure of the preform overlapping (configuration B) before and after failure

Concerning the detection of microcracks using RFID the results indicate that the influence of the initiated microcracks on the signals is too low (Figure 6). Microcracks were initiated for load levels higher than 30 kN, which corresponds to strain levels higher than 0.5%. There is an increase of the resistivity and of the impedance of 1 to 2% at these strain levels, which are not sufficient to be detected by the sender device.

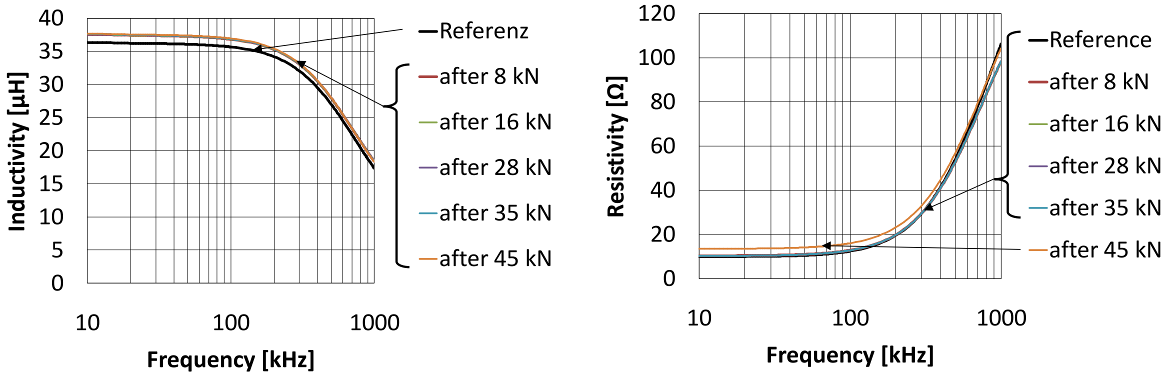

Figure 6 a, b. Inductivity and resistivity of the elliptical coil as to monitor crack initiation as a function of the load level

5. Outlook

One advantage of a RFID-monitoring system is that the carbon fiber sensor measures along its length, so the length and shape can be adapted to a specific monitoring example. In the case of monitoring the bond line of different structural elements, i.e. skin-stringers, the CFS can be meander shaped along the length of the edge of the bond line, which is shown in Figure 7 a, b. In this case a crocheting technique was applied to manufacture the CFS. This advanced manufacturing technique has the potential to keep the costs of the CFS-patch very low. Due to the wireless connection between transmitter and receiver no plugs or connectors are necessary. The whole receiver system can be protected by a cover to avoid any influence of environmental effects.

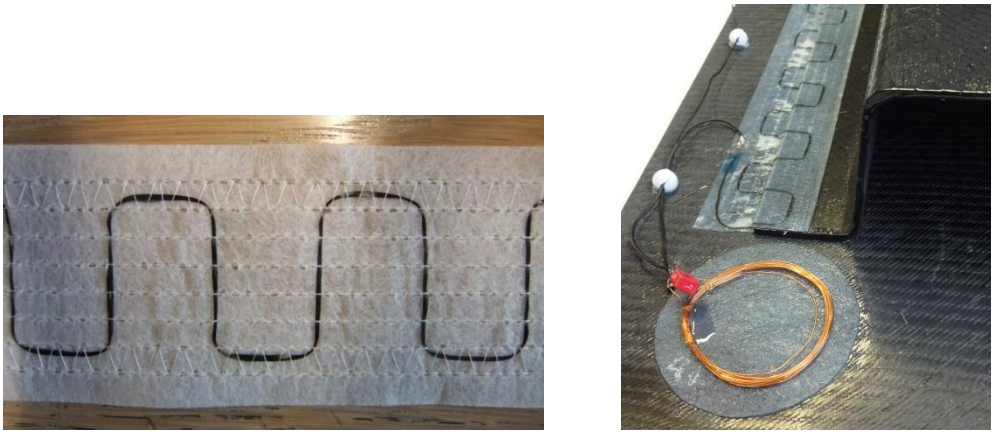

Figure 7 a, b. RFID device (transponder coil, capacitor and a CFS) to monitor the bondline of a skin-stringer configuration

6. Conclusions

A simple RFID-receiver, which consists of an antenna coil, a capacitor and a CFS, was characterized for damage monitoring of composite structures. The results show that the RFID-system is predestined to detect structural damages, when they have a strong effect on the specific electrical properties of the

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receiver device, which can be detected wirelessly by the transmitter device. The approach was verified for the failure of a preform overlapping. The shape and position of the CFS can be adapted to a specific monitoring problem. Even complex shaped CFS can be efficiently manufactured using advanced textile techniques, like crocheting. Due to the simplicity of the design, the RFID based damage detection system can be an alternative to other approaches based on microprocessor controlled intelligent sensor meshes for many applications.
One application can be the monitoring of adhesively bonded structures. The availability of a low-cost and adaptive system to monitor the durability of the bondline would improve the acceptance of this technology remarkably. If successful, the implementation of the research into practice would allow easily monitoring of the condition and performance of bonded structures. It can help with early detection of overstressed and damaged zones of structural elements, thus substantially reduce the cost of repair and increase the safety in many different industrial areas, i.e. civil engineering infrastructures.

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