Analyse dielektrischer Eigenschaften von Harzsystemen für CFK mittels Hochfrequenz-Wirbelstromverfahren

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Kurzfassung

Die Wirbelstrommesstechnik ist ein induktives Prüfverfahren, welches traditionell für die zerstörungsfreie Charakterisierung elektrisch leitfähiger Materialien eingesetzt wird [1]. Eine Erweiterung des dabei benutzten Frequenzspektrums bis in den Bereich von 100MHz, erschloss zudem Anwendungsgebiete wie die Prüfung an sehr schwach leitfähigen Materialien. Davon profitierte insbesondere die zerstörungsfreie Charakterisierung von CFK, dessen mittlere Leitfähigkeit nur etwa 1/1000 im Vergleich zu der von Aluminium beträgt [2]. Strukturanalysen, Defektoskopie und Grammaturbestimmung kohlenstoff-faserverstärkter Werkstoffe mittels HF-Wirbelstromverfahren gehören mittlerweile zum Stand der Technik [3].

Der Einsatz von Hochfrequenz-Wirbelstromtechnik an CFK bringt verstärkt Messergebnisse hervor, deren Informationsgehalt über die klassischen zu beobachtenden Eigenschaften wie elektrische Leitfähigkeit und Permeabilität des Materials hinauszugehen scheinen [4]. Die Ursache dafür wird in der kapazitiven Kopplung zwischen den Carbonrovings und dem daraus resultierenden Einfluss dielektrischer Effekte vermutet [5]. Die experimentelle Überprüfung zeigt jedoch die Unvollständigkeit dieser Hypothese. Auch ohne die Anwesenheit elektrisch leitfähiger Strukturen lassen sich verschiedene, nicht-leitfähige Materialien an Hand der komplexen Impedanzänderung der Messspule unterscheiden.

Eine Erklärung für dieses Phänomen findet sich in den Maxwell Gleichungen. Diese zeigen, dass eine Charakterisierung mittels hochfrequenter Wirbelstromtechnik prinzipiell auch an nicht-leitenden Materialien angewendet werden kann. Die Veränderung der komplexen Spulenimpedanz liefert dann Informationen zur Permittivität der Probe. Bei schwach leitfähigen Materialien mischen sich Einflüsse von Permittivität und elektrischer Leitfähigkeit. FEM Simulationen und Experimente stützen diese Erkenntnisse. So stimmt der zeitliche Verlauf der komplexen Impedanzänderung des Wirbelstromsensors während der Aushärtung des Epoxidharzes L20 gut mit der kapazitiv gemessenen Veränderung des Realteils der Permittivität der Probe überein. Dieser Einfluss der lokalen Permittivität eines

Materials ermöglicht neue Anwendungsgebiete der HF-Wirbelstrommethode, wie z.B. die Charakterisierung lokaler Aushärtefehler (Hot-Spots) an CFK.

Quellenangaben:

[1] DIN 54140
[2] Goeje, M.P. de; Wapenaar, K.E.D. (1992): Non-destructive inspection of carbon fibre-reinforced plastics using eddy current methods. Composites Vol. 23 (3), 147-157.
[3] www.carbon-fiber-testing.com
[4] Schulze, M. et al. (2010): High-resolution eddy current sensor system for quality assessment of carbon fiber materials. Microsystem Technologies Vol. 16 (5), 791-797.
[5] Lange, R.; Mook, G. (1994): Structural analysis of CFRP using eddy current methods. NDT & E International Vol. 27 (5), 241–248.

Analyzing dielectrical properties of resins used in CFRP with High-frequency Eddy Current Technology

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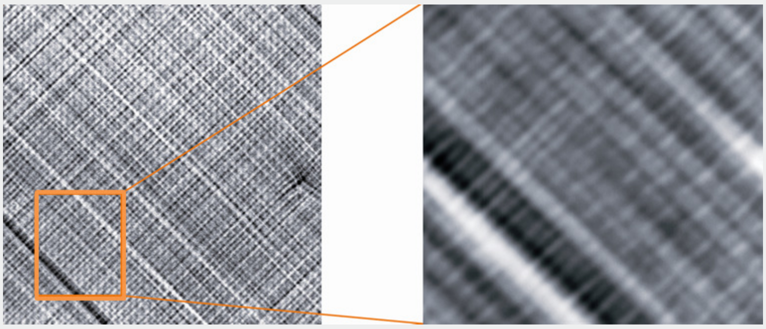


Outline

Introduction and Motivation

- Principles and Use of Eddy Current Measurements
- High-frequency Eddy Current Testing at CFRP

Influence of sample permittivity on EC measurement

- Theoretical background and FEM simulation
- Experimental results: Monitoring cure of resin L20
- Experimental results: Identifying „hot spots“ in CFRP

Conclusion

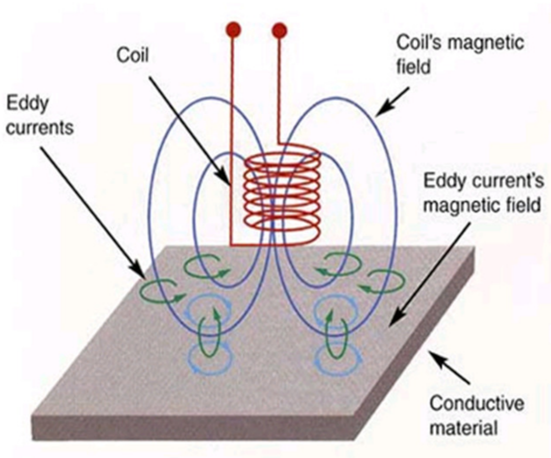
- Summarizing thoughts
- Acknowledgements and questions

Eddy Current Measurement is a well established approach for non-destructive testing

Use according to DIN 51140

Eddy current measurement is used…

"... um Inhomogenitäten und Werkstofftrennungen nachzuweisen oder Werkstoffeigenschaften zu ermitteln und/oder zu vergleichen, die **von der elektrischen Leitfähigkeit und/oder der Permeabilität** abhängen; …".



Development of High-Frequency Eddy Current Testing (up to 100 MHz) extended typical fields of application

With increasing measurement frequency…

….Penetration depth decreases

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

…Measurement signal gets stronger

$$U_{Ind} = \frac{-d\phi}{dt}$$

Improved testing of materials with low electrical conductivity, for example CFRP

Still reasonable penetration depth due to low electrical conductivity of the sample

- Conductivity Aluminum: $\sigma = 37 \cdot 10^6\ ^S/_m$
- Conductivity Carbon Fibre
  $\sigma = 5 \cdot 10^3$ bis $5 \cdot 10^4$ S/m (0° to Fibre)

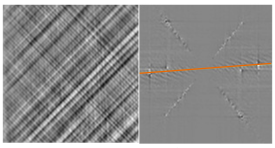
Standard penetration depth in CFRP:
- At 10 MHz: ~ 1mm
- At 1 GHz: ~0,1mm

Still a good measurement sensitivity despite low electrical conductivity of the sample

Increasing use of HF Eddy Current Testing at CFPR

Three main fields of application for HFEC on CFRP…

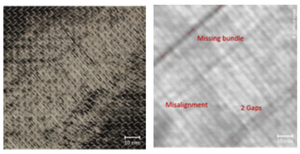
Analyzing Structure



30x30cm, misalignment of 5th layer by 2 °

Investigate fiber orientation of hidden CF layers, supported by 2D Fourier Transformation

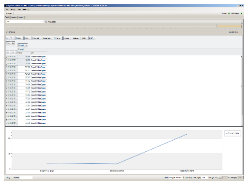
Detecting Defects



Picture and EC Scan, CF textil 10 x10cm

Distortion & Misalignment
Wrinkles & Overlaps
Gaps & Undulation
Impact & Delamination

Determining Local Grammage

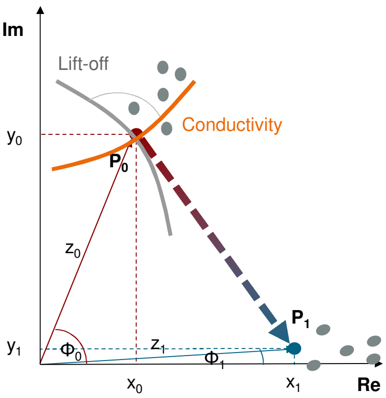


Monitoring and mapping local basis weight variations of carbon fiber textiles

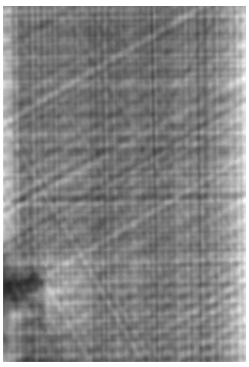
… sometimes also creating „surprising" measurement results

Ex. 1: Best visibility of delamination requires different phase rotation than best conductivity contrast

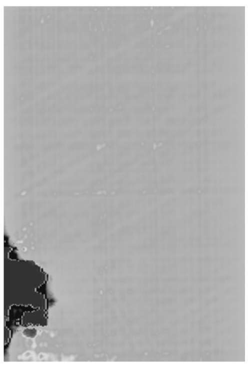
Phase rotation of complex impedance to get best contrast regarding local conductivity



„Re" of Z, mapped



„Im" of Z, mapped



Sample: 12-layer Laminate with delamination
(90°/0°/120°/30°/150°/60°/60°/150°/30°/120°/0°/90°)
b*h*t: 10*18*0.5cm

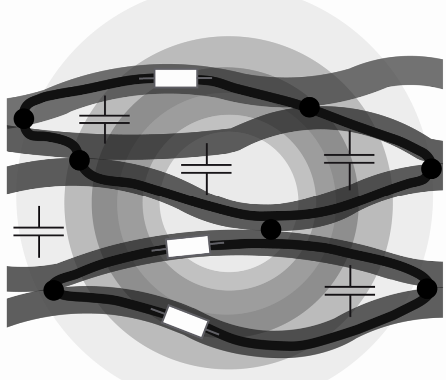
Explaination for those unexpected effects observed with EC on CFRP is seen in the structure of that material

Eddy Current on CFRP:
[Lange, R.; Mook, G. (1994)]

Permittivity of the matrix in CFRP additionally influencing eddy current signal

- Carbon Roving forming capacitive structures, influencing EC signal
- Capacity of those structures also depends on permittivity of the polymer matrix

Coils equipotential lines

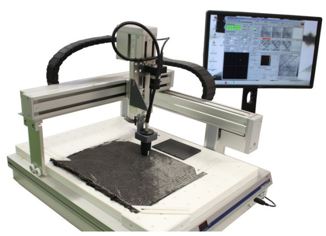


Eddy current model of CFPR, acc. to Lange/Mook

Own empirical research indicates that current theory on influence of sample permittivity needs to be extended

Measurement setup

- EddyCus CF map

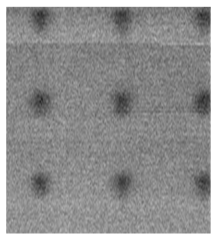


- Sensor T05

Sample (photography)

- POM (Polyoxymethylen) with holes(air)
- Rel. permittivity: 3,7 vs 1,0
- Sample size 9x10cm, hole diameter ~6mm

HF Eddy Current Scan



Permittivity of the sample also influencing EC signal when no capacitive structures are present

Step-back towards Maxwell equations show potential of HFEC for permittivity measurements

Maxwell equations*…. | **… Leading to the following main conclusions**

$$\vec{\nabla} \cdot \underline{\vec{D}} = \rho$$

$$\vec{\nabla} \cdot \underline{\vec{B}} = 0$$

$$\vec{\nabla} \times \underline{\vec{E}} = -j\,\omega\,\underline{\vec{B}}$$

A time varying magnetic field creates a rotating **electric field *E* independent of the conductivity of the sample**

$$\vec{\nabla} \times \underline{\vec{H}} = \underline{\vec{J}} + j\,\omega\underline{\vec{D}} = (\sigma + j\,\omega\,\varepsilon)\;\underline{\vec{E}}$$

Both, **eddy currents and displacement currents are influencing the coil's** magnetic field and therefor coil impedance.

Different phasing of conductivity vs. permittivity influences leading to unequal effect on coil impedance.

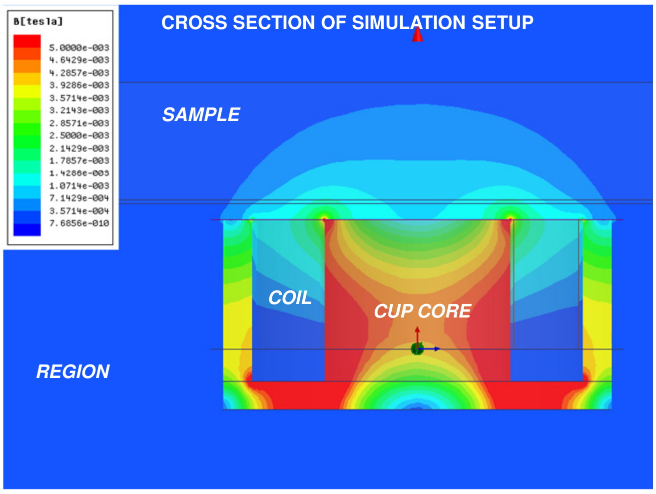
$$\vec{B} = \mu_0\mu_r\,\vec{H} \qquad \vec{D} = \varepsilon_0\varepsilon_r\,\vec{E} \qquad \vec{J} = \sigma\vec{E}$$

* version for constant frequencies

ANSYS FEM Simulation to doublecheck conclusions

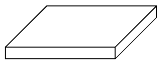
FEM simulation setup

- Ansys Maxwell, Eddy Current Solver
- Coil with cup core
  - stranded modelling
  - 28 windings
  - d_i = 4,7mm
  - h = 3,2mm
  - I_{ges} = 2,8 A, 10 MHz
- Different samples
  - 60x60x2mm
  - 0,4mm Lift-off
- Apaptive meshing until „energy error“ <0,1%

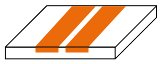


FEM Simulation confirms theoretical conclusions

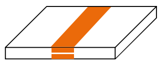
Homogenous polymer sample



Two carbon rovings within one layer



Two carbon rovings in different layers

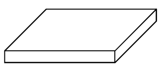


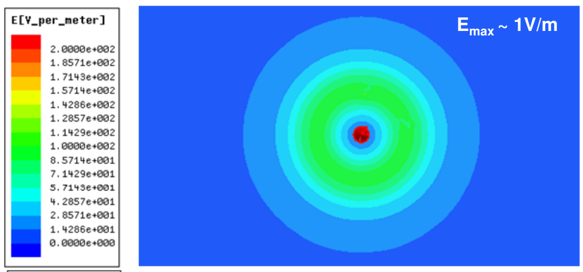
Key learnings

- Increasing sample **permittivity** leads to **rising magnitude of magnetic flux** within the coil
- Increasing sample conductivity leads to decreasing magnitude of magnetic flux within the coil
- Increasing **conductivity** of the sample also **decreases the effect of permittivity** on the magnetic flux (even relatively)
- **Capacitive structure** within one layer **can multiply** the effect of permittivity on the coil's magnetic flux (up to times 20)
- Capacitive structure between different layers do not strengthen the effect of permittivity

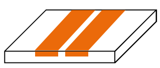
Example of simulation results: top view on sample

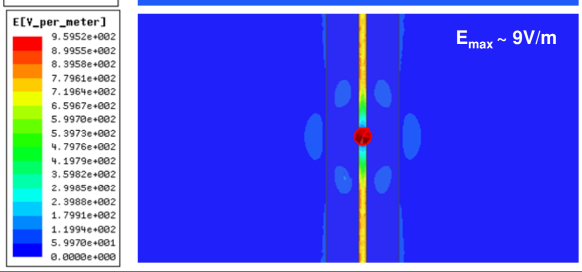
Homogenous polymer sample





Two carbon rovings within one layer





Influence of local permittivity on coil impedance opens new potential applications for HF EC technology

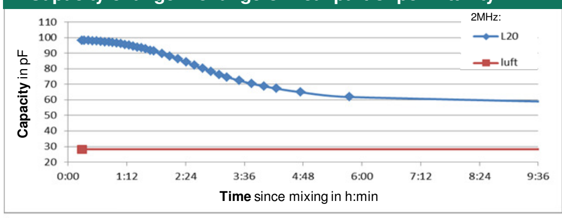
		Resin	CFRP	...
Monitoring permittivity change over time	▪ Cure monitoring ▪ Monitoring degradation/aging ▪	Ex. ①		
Mapping homogenity of permittivity	▪ Identifying local curing defects ▪ Finding local damages ▪		Ex. ②	
Quantitative permittivity control (via calibration -tbc)	▪ Measuring permittivity ▪ Volume content of dielectric ▪			

① Cure Monitoring of epoxy resin L20 at room temperature: Capacitive reference measurement

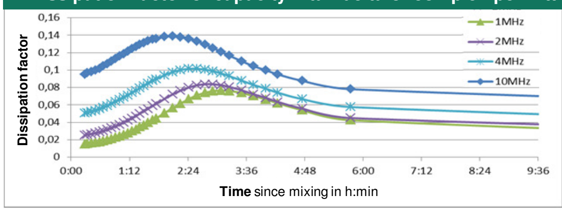
Reference Measurement setup

- LCR meter HP4275A
- Comb electrode IDEX Model 065S A/D Ratio 80
- Buildt within Faraday cage,

Capacity change ~ change of real part of permittivity

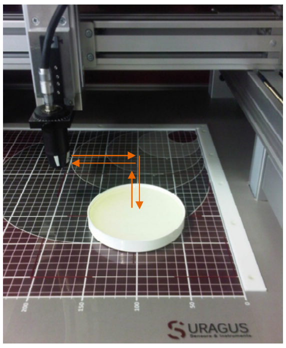


Dissipation factor of capacity ~ tan delta of complex permittivity



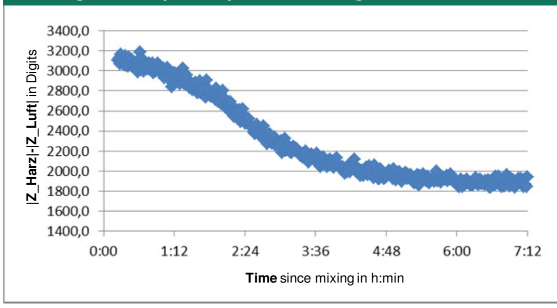
① Cure Monitoring of epoxy resin L20 at room temperature: High-frequency eddy current measurement

EC Measurement setup



- EddyCUS CF map 4040 with T05
- 1-point measurement with 1mm lift-off and seperate reference point (stand-by and calibration)

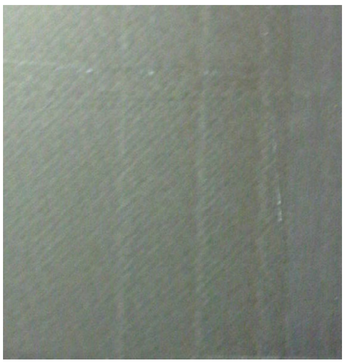
Change of complex impedance during cure



- **Change of magnitude of complex impedance with same charasterics as change of real part of permittivity**
- **Change of tan (δ) of permittivity not yet visible in eddy current measurement**

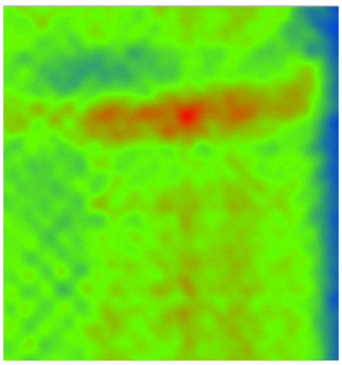
② Permittivity mapping to identify local curing defects in CFRP (hot spots)

Defect not visible at photography …



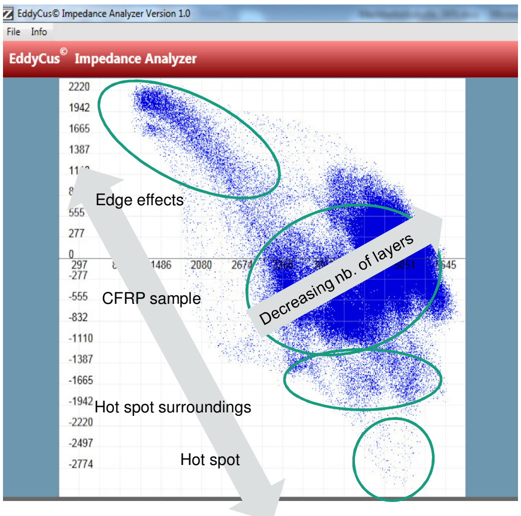
- CFRP sample (top view), 10x10cm
- Damaged induced by local overheating during cure

… but clearly visible at eddy current scan



- EC Scan with EddyCUS CF map and Sensor T05
- Induced damage visible, here red

② Permittivity mapping to identify local curing defects in CFRP (hot spots)



Key learnings (regarding that specific sample)

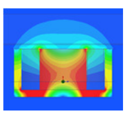
- Changes of CFRP thinkness, (which is a change in conductivity) can be clearly differentiated from the induced damages (permittivity change) analyzing the complex signal
- Edge effects and Lift-offs are more difficult to seperate from permittivity changes as both represent a shift of the complex signal on the same axis

Summarizing thoughts

General potential to characterize permittivity* of a sample using high-frequency eddy current technology was shown

$$\vec{\nabla}\cdot\vec{D}=\rho$$
$$\vec{\nabla}\cdot\vec{B}=0$$
$$\vec{\nabla}\times\vec{E}=-j\omega\vec{B}$$
$$\vec{\nabla}\times\vec{H}=\vec{J}+j\omega\vec{D}$$

Maxwell equations show **theoretical influence** of sample permittivity on coil impedance



Ansys **FEM simulation** confirms theoretical conclusions

Initial proof of concept using EddyCUS CF map for cure monitoring of resin L20 and permittivity mapping of local curing defects

* Real part of complex permittivity

Focus of further research

- **Proof of concept for other potential fields of application**, especially those where EC technology has clear advantages compared to other dielectric measurement methods
- Developement of **algorithms/procedures to simplify interpretation of measurment data**, esp. for CFRP
- Dedicated **sensor developement** for permittivity dominated measurement tasks

A big thanks to all sponsors of that research project

TECHNISCHE UNIVERSITÄT DRESDEN — …providing financial support through “Stipendium zur Förderung von Nachwuchswissenschaftlerinnen”

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SURAGUS Sensors & Instruments — …providing high-frequency eddy current measurement equipment and supporting with a lot of expertise

…supporting with a lot of expertise on eddy-current measurement and further non-destructive testing — Fraunhofer IZFP