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. 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. Strukturanalysen, Defektskopie und Grammaturbestimmung kohlestoffaserverstärkter Werkstoffe mittels HF-Wirbelstromverfahren gehören mittlerweile zum Stand der Technik.


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

Simone Gäbler, Henning Heuer, Martin Schulze
DGZIP-Jahrestagung, 28. Mai 2014 in Potsdam

Outline

| HF Eddy Current on CFRP | • Principles and Use of Eddy Current Measurements |
|                        | • High-frequency Eddy Current Testing at CFRP     |
| Characterizing permittivity with HF EC | • Theoretical background and FEM simulation |
|                                      | • Influence of permittivity on complex impedance Z |
|                                      | • Potential applications – first experimental results |
| Conclusions and outlook | • Summarizing thoughts |
|                        | • Acknowledgements and questions |

High-frequency Eddy Current Technology

Simone Gäbler, Henning Heuer, Martin Schulze

Characterizing permittivity with HF EC

• Theoretical background and FEM simulation
• Influence of permittivity on complex impedance Z
• Potential applications – first experimental results

Conclusions and outlook

• Summarizing thoughts
• Acknowledgements and questions
Eddy Current Measurement is well established for NDT of electrically conductive materials

- Used to characterize inhomogeneities or sample properties depending on electrical conductivity and/or magnetic permeability [DIN 51140]
- Non-contact measurement
- Penetration depth can be actively influenced by measurement frequency: 10kHz-100MHz
- Highly sensitive
- High speed: 50,000 measurements per second
- Real-time measurement possible

Complex impedance allows phase rotation of EC images

<table>
<thead>
<tr>
<th>Complex Impedance Z</th>
<th>Derived EC-Scan</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>( P_0 ) : Eddy current value at a given frequency in air</td>
<td></td>
</tr>
<tr>
<td>( P_1 ), ( P_x ) : Complex Eddy current signal of a sample within the field</td>
<td></td>
</tr>
<tr>
<td>Crack detection: EC-Scan overlay with test sample</td>
<td></td>
</tr>
<tr>
<td>o For each imaginary value a certain level of gray is assigned</td>
<td></td>
</tr>
<tr>
<td>o Values are positioned according to location of measurement</td>
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</table>
Developement of High-frequency EddyCus Testing (up to 100 MHz) in the frequency range of radio waves

- Developed in 2007 by former Fraunhofer IZFP, Dresden branch
- Commercialized by the spin-off Suragus in 2010

Higher frequency extends typical fields of application

With increasing measurement frequency...

...Penetration depth decreases

\[ \delta = \frac{2}{\omega \mu \sigma} \]

...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 of Aluminum: \( \sigma = 37 \cdot 10^6 \frac{S}{m} \)
- Conductivity of 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: \( \sim 1 \) mm
- At 1 GHz: \( \sim 0.1 \) mm

Still a good measurement sensitivity, despite low electrical conductivity of the sample
There are three main fields of application for HF Eddy Current Measurement on CFRP

1. Analyzing Texture
   - Investigate fiber orientation of hidden CF layers, supported by 2D Fourier Transformation

2. Detecting Defects
   - Distortion & Misalignment
   - Wrinkles & Overlaps
   - Gaps & Undulations
   - Impacts & Delaminations

3. Determining Local Grammage
   - Monitoring and mapping local basis weight variations of carbon fiber textiles

Texture analysis on CFRP with HF EC technology
(source: Suragus)

- EC Scan
  - CFRP plate with stringer
  - 270 x 200 mm²
  - @ 0.2 x 0.2 resolution

Advanced image processing:
Layer separation of differently oriented plies

Histogram of orientation
2. Defect detection with HF Eddy Current – in-plane wave detection

<table>
<thead>
<tr>
<th>EC-Scan of Aircraft CFRP structure</th>
<th>EC-Scan filtered to -45° orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
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</table>

- Out-of-plane wave
- In-plane wave

3. Determining local areal weight of CF textiles with HF EC (source: Suragus)

<table>
<thead>
<tr>
<th>EddyCus CF inline BW</th>
<th>Quantitative grammage determination</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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</table>

- Time stamp or trigger controlled
- Monitoring via network
HF EC Measurement can be used not only on electrically conductive, but also on insulating samples

Measurement setup
- EddyCus CF map

Sample (photography)
- POM (Polyoxymethylene) with holes (air)
- Rel. permittivity: 3.7 vs 1.0
- Sample size 9x10cm, hole diameter ~6mm

HF Eddy Current Scan

Permittivity of the sample is influencing EC signal
Step-back towards Maxwell equations show potential of HF EC for permittivity measurements

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

\[ \nabla \cdot \vec{D} = \rho \\
\nabla \cdot \vec{B} = 0 \\
\nabla \times \vec{E} = -j \omega \vec{B} \]

A time-varying magnetic field creates a rotating electric field \( E \) independent of the conductivity of the sample.

\[ \nabla \times \vec{H} = \vec{J} + j \omega \vec{D} = (\sigma + j \omega \varepsilon) \vec{E} \]

Both, eddy currents and displacement currents are influencing the coil’s magnetic field and therefore the coil impedance.

\[ \vec{B} = \mu_0 \mu_r \vec{H} \quad \vec{D} = \varepsilon_0 \varepsilon_r \vec{E} \quad \vec{J} = \sigma \vec{E} \]

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

Ansys Maxwell FEM Simulation confirms theoretical conclusions

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 20 times).
- Capacitive structure between different layers do not strengthen the effect of permittivity.

**Fraunhofer**

**URAGUS** Sensors & Instruments

**Technische Universität Dresden**

**Leibniz Universität Hannover**
Example of simulation results: top view on sample

- Homogeneous polymer sample
- Two carbon rovings within one layer

Experimental evidence: Influence of permittivity on complex impedance Z

- Samples (Ø 10cm) with copper films (15nm-1000nm)
- Average Complex Impedance [in digits]

- Samples with air, ε = 1
- Sample + dielectric foil, ε ~ 3
- CF map 4040, Sensor Sura T05
Permittivity increase causes angle of shifting slightly.

Average Complex Impedance

Sensor Sura T05, CF map 4040

-17-

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

| Monitoring | Cure monitoring | Monitoring degradation/aging | Monitoring permittivity change over time | Ex. 1 |
| Mapping homogeneity of permittivity | Identifying local curing defects | Finding local damages | Ex. 2 |
| Quantitative permittivity control (via calibration) | Measuring permittivity | Determining base weight and resin content in parallel. | Ex. 3 |

Conclusions
(for used measurement setup)
- Permittivity increase causes decrease of magnitude of complex impedance
- Shifting of measurement value along axis of about -75°
- Angle of shifting slightly depends on conductivity of the sample
- > with increasing sample conductivity differentiation between permittivity and conductivity related effects gets more difficult
Cure Monitoring of epoxy resin L20 at room temperature:
Capacitive reference measurement

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

Cure Monitoring of epoxy resin L20 at room temperature
with High-frequency eddy current device

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

Change of complex impedance during cure...
2 Permittivity mapping to identify local curing defects in CFRP (hot spots)

Defect not visible at photography ... … but clearly visible at eddy current scan

- CFRP sample (top view), 10x10cm
- Damage induced by local overheating during cure
- EC-Scan with EddyCus CF map and Sensor Suragus T05
- Induced damage visible (red)

Key learnings
(regarding this specific sample)

- Changes of CFRP thinkness, (which is a change in conductivity) can be clearly differentiated from the induced damages (permittivity change) by analyzing the complex signal
- Edge effects are more difficult to separate from permittivity changes
### Detecting / Imaging of thermal degradation on CFRP used in aerospace

**EC Measurement setup**

- CFRP sample* as used in production of military helicopters (e.g. Tiger, NH90)
  - Hexcel Prepreg M18-1/G939
  - 250x125mm
  - Layer design: \((0^\circ/45^\circ/90^\circ/45^\circ)_3\)
  - Thermal damage through 400°C hot air for 90 min

*Thanks to M.Sc. A. Floet for sample preparation

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<td>EC-Scan</td>
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<td>Photography</td>
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### HF Eddy Current on CFRP

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

### Characterizing permittivity with HF EC

- Theoretical background and FEM simulation
- Influence of permittivity on complex impedance \(Z\)
- Potential applications – first experimental results

### Conclusions and outlook

- Summarizing thoughts
- Acknowledgements and questions
### Summarizing thoughts

- **General potential to characterize permittivity** of a sample using high-frequency eddy current technology was shown
  - Maxwell equations show theoretical influence of sample permittivity on coil impedance
  - Ansys FEM simulation confirms theoretical conclusions
  - Feasibility of EddyCus measurement to detect permittivity changes was shown for a first set of potential applications

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<th>S. IKT</th>
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### 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
- Dedicated sensor development for permittivity dominated measurement tasks

### A big thanks to all sponsors of the research project

- **Technische Universität Dresden**
  - ...providing financial support through “Stipendium zur Förderung von Nachwuchswissenschaftlerinnen”

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  - ...sponsoring sample production and supporting with a strong material expertise, esp. Prof. Heinrich and Mr. Spickenheuer
  - ...providing high-frequency eddy current measurement equipment and supporting with a lot of expertise

- **Fraunhofer | IKT**
  - ...supporting with a lot of expertise on eddy current measurement and further non-destructive testing, esp. Prof. Heuer
Questions?

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