Microwave Testing (µT): An Overview

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1. Introduction

Nondestructive testing (NDT) comprises noninvasive techniques to determine the integrity of a material, component or structure or quantitatively measure certain characteristic of an object. According to the detailed task, various physical methods are used, mostly based ultrasound, Xray, eddy current, and acoustic emission, supplemented by visual testing.

Because the demand for NDT in general and especially for dielectric (= electrically non-conducting) materials has increased and because meanwhile microwave technology is used in consumer products and therefore has become less expensive, NDT with microwaves is growing. Therefore in 2011 the Fachausschuss Mikrowellen- und Terahertzverfahren (FA MTHz) of the Deutsche Gesellschaft für Zerstörungsfreie Prüfung (DGZfP) and in 2014 the Microwave Testing Committee of the American Society for Non-Destructive Testing (ASNT) have been founded. Work on standardization of Microwave Testing is beginning.

2. Physical and technical basics of microwave testing

Just as light and X-rays so microwaves are electromagnetic waves. Their frequencies extend from 300 MHz to 300 GHz and are situated between the radio waves and the far infrared, see fig. 1. (The transition region to the far infrared sometimes is called THz region). The free space wavelengths range from 1 m to 1 mm and are of "handy" dimensions.

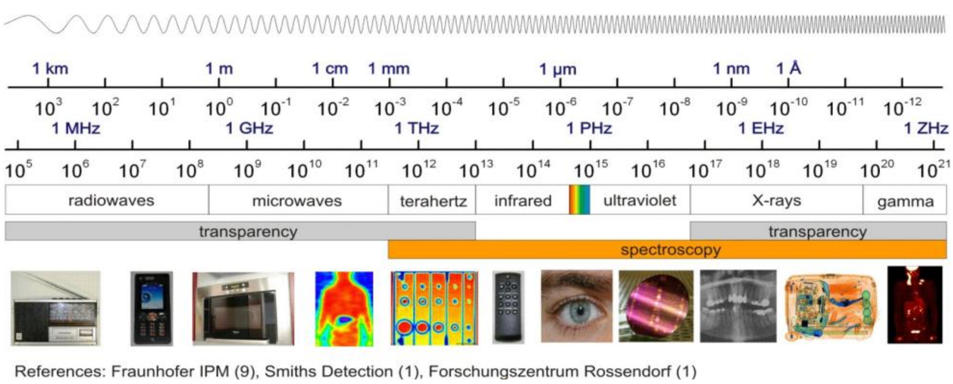


Figure 1: Electromagnetic spectrum

With respect to the frequencies of the above mentioned standard NDT methods, microwave testing is situated between eddy current testing and visual or X-ray testing, respectively.

In the situation of fig. 2 we visually recognize the different types of material, namely air, glass, liquid, and gas of the bubbles. This is because of their different refractive indices *n* and subsequent phenomena like diffraction, refraction, and reflection. These also are the basis for microwave testing. However, in the microwave region one characterizes material by its relative permittivity (dielectric constant) $\varepsilon_r = n^2$. That means, in principle microwave testing means display of local variations of the relative permittivity in dielectric (= electrically non-conducting) material.

Figure 2: Champagne glass

Microwave testing can be performed in the reflection mode and in the transmission mode, see fig. 3.

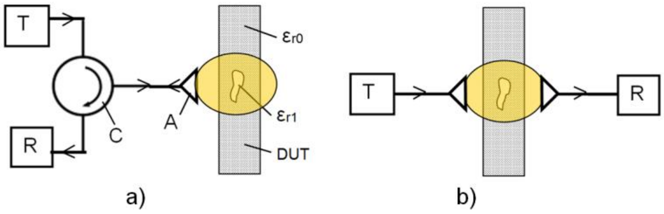


Figure 3: Microwave testing in the a) reflection mode and in the b) transmission mode.
T – transmitter, R – receiver,
C – circulator, A – antenna,
DUT – device under test

In the reflection mode, fig. 3a, the microwave path extends from the transmitter T through the so-called circulator C to the antenna A which radiates into the device under test DUT. The reflected signal is received by the antenna again, separated from the transmitted signal in the circulator, transferred to the receiver R, and there evaluated with respect to magnitude and phase. According to the average permittivity in the illuminated region within the DUT the signal is reflected stronger or weaker and with varying phase. In this way by scanning over the DUT surface local variations of the permittivity are recognized and so material defects.

In the transmission mode, fig. 3b, the signal is evaluated which is transmitted through the DUT. There has to be access to the backside of the DUT.

Depending on the antenna design the microwave beam is more or less focused and such is the spatial resolution accordingly high or low.

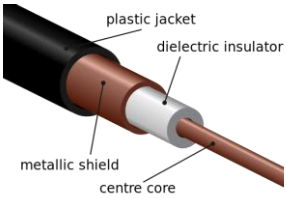
Eddy currents cannot be used to test dielectric materials, because their electrical conductivity is zero. Compared to ultrasonic testing microwave testing is advantageous if sound-absorbing materials or large observation depths are concerned. X-ray based testing is the highest-performance NDT method. However, often it is not in use because of its high safety effort. Microwave testing does not need this safety effort and therefore is less expensive.

3. Applications of microwave testing

Microwave NDT can be used for the detection of flaws or discontinuities, the determination of material properties, condition monitoring, and also in metrology.

3.1 Detection of flaws

The antennas (= probes) normally are based on typical microwave transmission lines, see fig.4.



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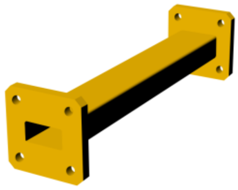
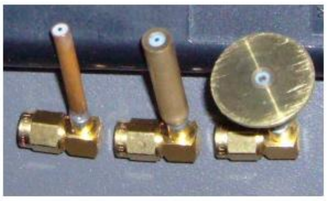


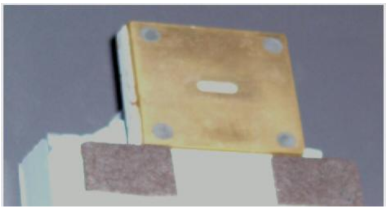
b)

Figure 4: Typical transmission lines for microwaves
a) Coaxial line
b) Rectangular waveguide

The coaxial line, fig.4a, consists of a metallic centre core and a metallic shield, both concentric. At high frequencies often the attenuation is too high. Then waveguides are used. These are metallic tubes, e.g. with rectangular cross section as in fig. 4b. Such a waveguide can only transmit waves with frequencies above a certain cutoff frequency. This depends on the cross sectional dimensions



a)



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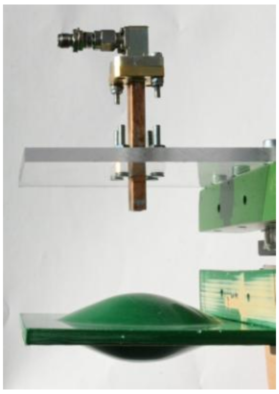


c)

Figure 5: Microwave probes. a) Coaxial antenna. b) Waveguide antenna with iris. c) Lens antenna with open ended rectangular waveguide as primary radiator.

Fig.5 shows typical probes for microwave NDT. Fig. 5a shows probes based on coaxial lines. These antennas mainly scan the DUT within the microwave near field. So they have observation depths in the order of 1 to 2 wavelengths. However, they offer a transversal spatial resolution, which is much sharper than the wavelength and mainly depends on the antenna dimensions.

Fig. 5b shows a probe based on a rectangular waveguide with an additional iris at the open end. Normally waveguides have a larger observation depth than coaxial lines, but the lateral spatial resolution is somewhat coarser.

Fig. 5c shows a lens antenna, in which the primary radiator is an open ended waveguide which radiates through the microwave lens (green). The microwave beam is focused in the depth of the DUT. The lateral resolution can be in the order of a wavelength, even deep within the DUT. An observation depth of 60 mm has been demonstrated in glass-fiber reinforced plastic (GFRP). This probe type, however, is rather voluminous.

3.1.1 Local and mechanically scanning procedures

Fig. 6 shows a simple hand-held instrument for microwave NDT. It consists of the display and control module and the probe module. The displays of indications are similar as in eddy current testing.

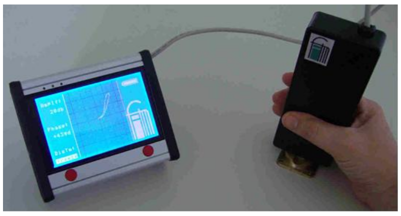


Figure 6: Hand-held microwave NDT instrument

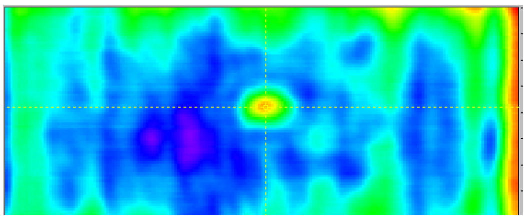


Figure 7: Wall of GFRP pipe. C-scan of a flaw in a depth of 60 mm, 24 GHz

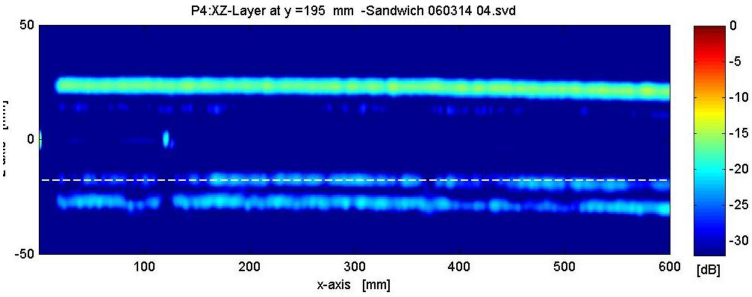
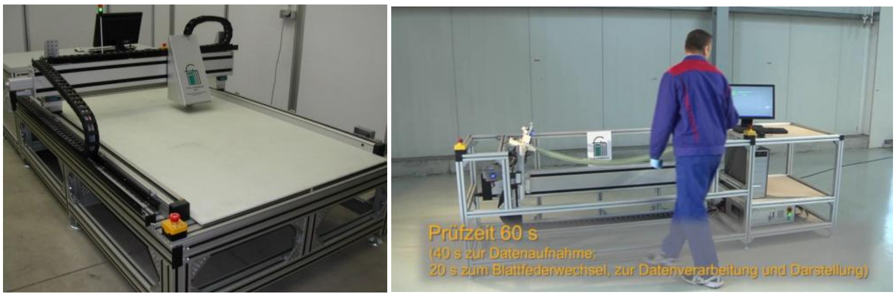


Figure 8: B- scan of a foam/GFRP sandwich at 100 GHz. The indication at 120 mm results from moisture at the interface between foam and GFRP in a depth of about 35 mm. (Becker, Keil: Jahrestagung DGZfP 2017, paper Mi3C2)

Test systems with automatic, e.g. meander type scanning can present the results as C-scans (2-D view on the DUT surface), see fig 7. With high microwave frequencies also B-scans (cross sectional view) with remarkable depth resolution are possible, see fig. 8.

Stationary microwave test systems generally are adjusted to the respective task, see fig. 9.



a) b)

Figure 9: Stationary microwave test systems for a) planar substrates, b) GFRP leaf springs for automobiles.

3.1.2 Direct imaging procedures

Scanning procedures with moving probes are time consuming, even in the case of fig. 9b, in which two arrays with each 30 single probes are used and a cycle time of 60 seconds was realized. Direct imaging test procedures like X-ray through-transmission or thermography, but with microwaves, often would be more attractive.

Fig. 10 shows a stationary system, which does not scan with moving parts but only scans electronically. This body scanner is for the security test of persons, e.g. at airports. It is to be mentioned, that microwave radiation is not ionizing, in opposite to X-rays. Therefore the safety measures of X-ray testing, which are necessary to protect humans, are not necessary when testing with microwaves.

Figure.10: The body scanner R&SR®PS uses frequencies between 70 GHz and 80 GHz with a radiation power of 1 mW and each 3008 transmit and receive antennas. One after the other the antennas and 128 frequency channels are activated. This leads to a scan time as low as 32 ms.
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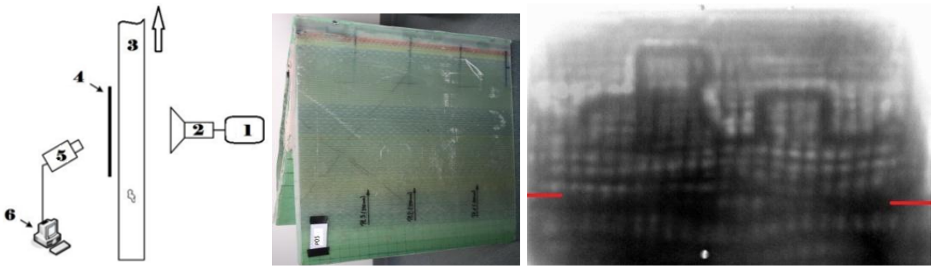
Another direct imaging microwave test procedure is the NIDIT procedure (NIDIT – Non-Ionizing Direct Imaging Testing). Fig. 11a shows the function principle. The **microwave source** (1) feeds **the antenna** (2) which irradiates the **DUT** (3) with a widespread beam. The radiation is uniformly incident on the DUT, there affected by the flaws, and accordingly non-uniformly incident on the **microwave absorbing foil** (4). Thus on the foil a non-uniform heat distribution is generated which corresponds to the flaw distribution and which is immediately detected by an **infrared camera** (5) and displayed on a **computer** (6). In this configuration the microwave absorbing foil 4 and the infrared camera 5 act as the microwave detector. If the DUT is moved videos can be generated.



a) b) c)

Figure 11: The direct imaging NIDIT procedure: a) principle view, b) sample DUT: cutout of the trailing edge of a rotor blade, c) single video frame of b) with distribution of adhesive

As an example DUT, fig. 11b shows the cutout of a rotor blade trailing edge of a wind turbine. The distribution of the inner adhesive, which cannot be seen visually, is to be visualized. Fig. 11c as a single frame of a video shows the NIDIT through-transmission image of this trailing edge. The test is performed as a blind test with artificial adhesive distribution. The DUT thickness in the situation of fig. 11c is about 20 cm.

3.2 Material properties, condition monitoring, metrology

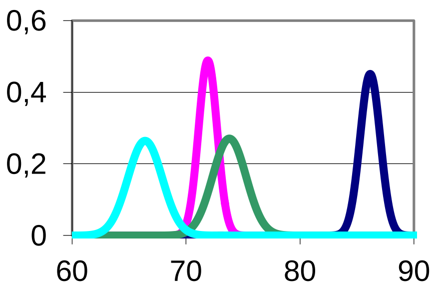
In the last decades various microwave methods have been developed to determine material properties of dielectric samples in the lab. For example samples are cut and inserted into waveguide sections with subsequent measurement of typical microwave parameters using a so-called vector network analyzer. The following evaluation results in permittivity and attenuation properties of the material.

Probes which are to be placed on fiber composite's surfaces to measure the fiber direction or the fiber-matrix-ratio are under development.

Not only in technical components but also in buildings determination of moisture often is done with microwaves.

In certain tasks the condition monitoring is easily possible with microwaves. Fig. 12 shows an example: In the final inspection of a ball valve it is to be ensured that after the assembling the valve a critical gasket is built-in (completeness check). Visual testing is not possible.


a)



b)

Figure 12: Checking the presence of a gasket in a plastic ball valve using phase measurements of an attached microwave probe. a) photo of the gasket. b) statistical evaluation of about 100 measured valves with and without gasket. Horizontal: phase (in degree) of reflection coefficient. Vertical: probability of the occurrence of the phase. Dark blue: without gasket. Turquoise, pink, green: with gasket from different material.

The solution of the problem is a microwave probe, which is placed outside onto the ball valve at the respective location, and the measurement of the phase of the reflection coefficient. Fig. 9b shows, that using a threshold of 81° the yes/no decision can be made with a high confidence level.

Microwave testing also lends itself for dimensional metrology, e.g. for wall-thickness and layer-thickness measurements. Wall-thickness measurements of dielectric tubes and pipes can be done by attaching to them a microwave probe from the outside and measuring the reflection coefficient. Fig. 13 shows an example. Fig.13b shows the calibration spiral, which extends inwards from wall thickness of 4.9 mm to 9.6 mm. During measurements, using this curve current measurement values of the reflection coefficient can be ascribed to the wall thickness values.

a)

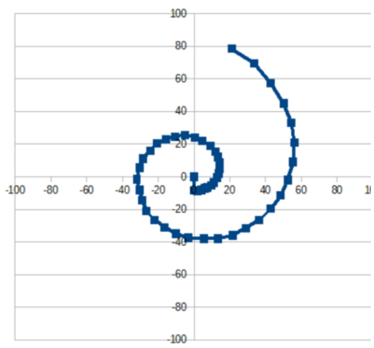

b)


Figure13: Wall thickness measurements of tubes from Thermoplastic Copolyester Elastomere (*TPC-ET*). a) photo of a pipe section, diameter about 60 mm. b) calibration spiral for thickness measurements between 4.9 mm and 9.6 mm. The graph shows the complex reflection coefficient measured with a microwave probe attached on the tube.

A further example of microwave based dimensional metrology is the FSC, which can be used to non-destructively measure the paint thickness on carbon composites (CFRP). These materials are of special use in the aerospace sector. Previously used instruments based on ultrasound or eddy currents can only be used unreliably or not at all for paint thickness measurements on CFRP.

a)  b) 

Figure14: Thickness gauge FSC for the non-destructive determination of paint thickness on carbon composites.
a) overview.
b) zoomed image with microwave module (green) and control and display module (black)

Fig. 14 shows the FSC, in use for paint thickness measurement on a CFRP aerobatic aircraft. Meanwhile the instrument is in regular use in the manufacturing and maintenance processes of widebody and further aircrafts.

4. Conclusions

Microwave testing (µT) is regarded as an emerging method to test dielectric, i.e. non-conducting materials and devices. There are a significant increasing number of microwave applications in practice and increasing research and development activities. Imaging of indications mostly is done by mechanical scanning. But body scanners already make use of electronic scanning to realize a direct imaging method. The further direct imaging method NIDIT is under development. Beyond the detection of flaws, microwave testing lends itself for the determination of certain material properties, for condition monitoring and dimensional metrology. – Standardization work is beginning.

5. Further References

- Joseph T. Case, Shant Kenderian: MWNDT – An Inspection Method, Materials Evaluation, March 2017, 339-346. (This paper has many references regarding microwave testing.)
- Reza Zoughi: Microwave Non-Destructive Testing and Evaluation, Kluwer Academic Publishers, 2000