fitm Hinken Consult

Mono-frequency microwave testing with B-scan presentation

Johann H. Hinken, fitm Hinken Consult, Magdeburg, Germany

Introduction

Non-destructive testing with microwaves is used for the inspection of electrically insulating, i.e. dielectric materials. Microwaves are electromagnetic waves with frequencies between 300 MHz and 300 GHz. They include millimeter waves and above about 100 GHz they are also called Terahertz waves. Concerning the spatial distribution of defects a microwave scan on the surface of a device under test first gives only the lateral distribution. A microwave transmission test gives no depth information. A microwave reflection test can be performed using the FMCW (Frequency Modulated Continuous Wave) method. This method uses the frequency difference between momentary transmit and receive signal to determine the depth of a defect. The application of the FMCW method requires a frequency band of significant width. Such a broad band only is available at high frequencies, i.e. from about 100 GHz upward. – This contribution shows how depth information with subsequent B-scan presentation can be obtained when using only a single frequency.

Principle

Fig. 1 shows the principle arrangement for microwave scanning in the reflection mode.

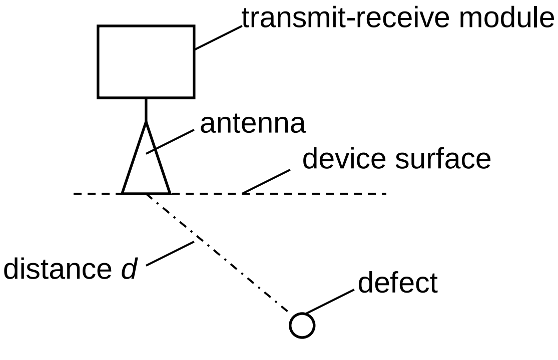

Figure 1: Microwave testing in the reflection mode

A transmit-receive module with an antenna is moved over the device surface *(x,y)* across a defect, which in this case is a dielectric inhomogeneity. The purpose is to detect the defect. To perform this the microwave oscillation is generated in the transmitter, radiated from the antenna, reflected from the defect, received by the antenna as a complex signal *R(x,y)* and further processed in a computer. The transfer function from the antenna to the defect is basically given by

$$U = \frac{1}{d} e^{-jkd} \qquad (1)$$

with the distance *d* between antenna and dielectric inhomogeneitiy with the relative permittivity ε_d, the wavenumber $k = 2\pi f \sqrt{\varepsilon_r}/c_0$, the frequency *f*, the relative permittivity ε_r of the material between the antenna and the defect, the imaginary unit $j = \sqrt{-1}$ and the speed of light c_0. The path *d* is travelled back and forth, i.e. two times. The strength of the received signal is proportional to the local reflection coefficient of the defect in its surrounding. This local reflection coefficient is proportional to the difference in permittivities $(\varepsilon_d - \varepsilon_r)$ and to the volume of the defect.

Fig. 2 shows the curve of *R(x,y)* during a scan along a line across the inhomogeneity. It is assumed that a zeroing on a position without defect was done before. Then the deflection is maximum when the distance *d* is minimum, i.e. when the antenna is directly above the defect. The length of the vector to the maximum deflection is a measure for the strength of the inhomogeneity, its angle to the real axis corresponds to the depth of the inhomogeneity.

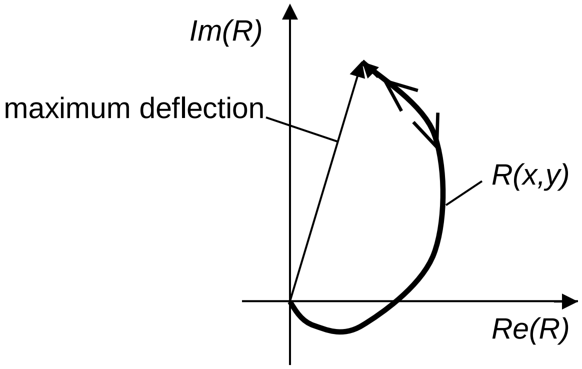

Figure 2: Curve of measured reflection coefficient *R(x,y)* when approaching and leaving the defect

If the defect not only consists of a localized dielectric inhomogeneity but of a distributed inhomogeneity with a distributed reflection coefficient $vi(\overrightarrow{r'})$ with the spatial vector $\overrightarrow{r'}$ within the space V', the complex received signal $R(x,y)$ at the point *x,y* of the device surface is

$$R(x,y) = \int vi(\overrightarrow{r'})\, U^2(d)\, dV' \qquad (2)$$

In eq. (2) the distance is

$$d(m',n',p',m,n) = \sqrt{(x'-x)^2 + (y'-y)^2 + z'^2} \qquad 3)$$

with z‘ being the depth of the inhomogeneity voxel.

In case of a digitized data acquisition and evaluation eq. (2) converts into

$$R(m,n) = \sum_{m',n',p'} DI(m',n',p')\ \ U^2(d(m',n',p',m,n)) \qquad (4)$$

In eq. (4) the pixel numbers *m* and *n* describe the antenna position in *x* and *y* direction. The voxel numbers *m', n'*, and *p'* describe the lateral and the depth position of the respective voxel with the local reflection coefficient *DI(m',n',p')*.

The objective now is to find voxels with non-zero local reflection coefficients *DI* and determine their location and the strength of their local reflection coefficient. That means, for voxels with $DI(m',n',p') \neq 0$ their location (m',n',p') and their magnitude $|\ DI(m',n',p')\ |$ are to be determined. This is approximately performed in the following way.

According to eq. (1) the magnitude of the transfer function *U* is maximum when *d* is minimum. According to eq. (3) this is the case for $m = m'$ and $n = n'$, i.e. if the antenna is placed directly over the pixel (m', n'). Now, the right hand side of eq. (4) approximately is simplified by neglecting all summands except those with $m = m'$ and $n = n'$. This yields

$$R(m,n) \sim \sum_{p'} DI(m,n,p')\ \ U^2(d(m,n,p',m,n)) \qquad (5)$$

With the transfer function

$$U(d(m,n,p',m,n)) = \frac{1}{p'\Delta z} e^{-j\,k\,p'\Delta z} \qquad (6)$$

and the voxel thickness Δz. This relation is used to evaluate the measured distribution of the reflection coefficient $R(m,n)$. It is considered that the local reflection coefficient $DI(m,n,p')$ is a real quantity. It can be positive or negative depending on ε_d being smaller or larger than ε_r. In the following it is first considered as positive. This often is the case, i.e. for pores or lack of resin in glass-fiber reinforced plastic (GFRP). Then the factor U^2 in the summands of eq. (5) is calculated with the correct *p'* if U^2 has the same phase as the respective *R(m,n)*. In this way the correct *p'* could be determined analytically. Here in the following a somewhat different way is used:

On trial, the measured reflection coefficient *R* at the position *(m,n)* is divided by the squares of the transfer function according to eq. (6) at different depths *p'Δz*. Because *DI* is positive real, at the correct depth this gives a positive real value. The falser the depth, the smaller is the real part. Therefore in a practical realization for each *p'* the real part of this quotient is registered and displayed together with the trial depth. A negative real part is suppressed. The real part is maximum at the correct depth.

Example

Fig. 3 shows a very inhomogeneous GFRP slab which is cut out from a boat hull. The slab has a very irregular backside and in its scan area of 140 mm x 100 mm it is 14 mm to 18 mm thick. Approximately at medium depth there is a strip-type resin enrichment, together with a delamination. At the backside and approximately in the center of the scan area there is the artificial flat bottom hole no. 2. The scan is performed at 5.8 GHz.

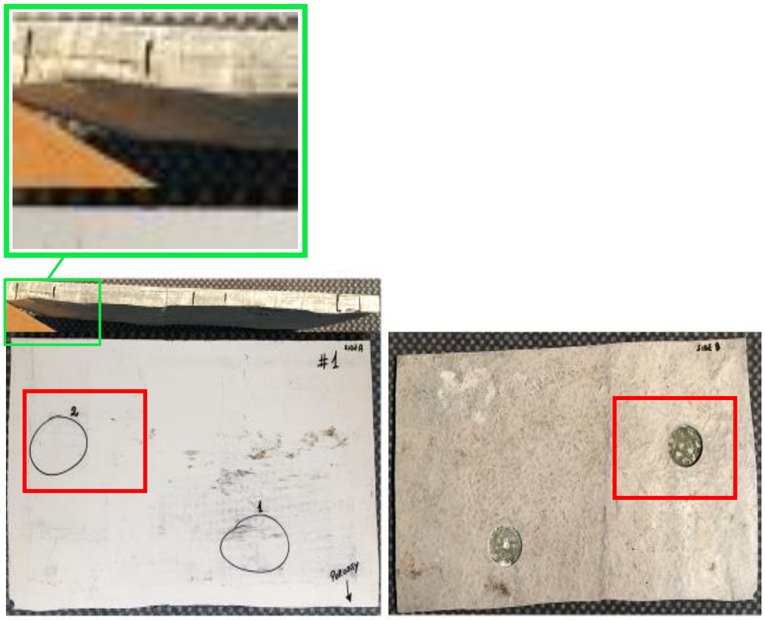

Figure 3: Cut out of boat hull. Left: Top and side view with detail magnification of the resin enrichment (green) and scan area (red). Right: Backside view

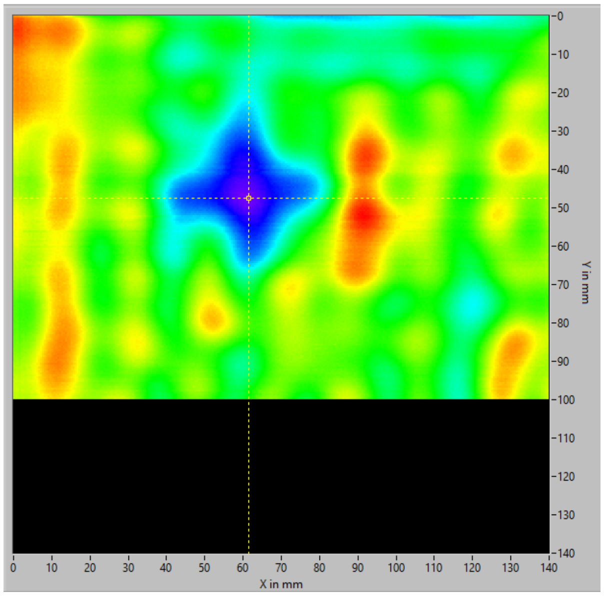

Figure 4: C-scan of cut out of boat hull. x: horizontal, y: vertical

Fig. 4 shows the customary C-scan of the measured reflection coefficient *R(x,y)*. The indication of the flat bottom hole is clearly seen in blue. However, at first the depth from which this indication and the other indications originate cannot be determined.

The same values of the measured reflection coefficient R(x,y) were also used for the evaluation according to the described procedure. Fig. 5 as a first result shows cross sectional views, i.e. B-scans.

Figure 5: Scan results displayed as B-scans, not to scale. From left to right: coordinate y near to top edge, medium, and near to bottom edge of fig. 4.

At the left edge of the three pictures at medium depth the continuous resin enrichment can be seen. The middle picture dominantly shows the flat bottom hole at the back side of the slab. The residual indications originate from further dielectric inhomogeneities and geometrical deviations from the back side. The blackness corresponds to the magnitude of the respective local reflection coefficient, i.e. the length of the vector in fig. 2.

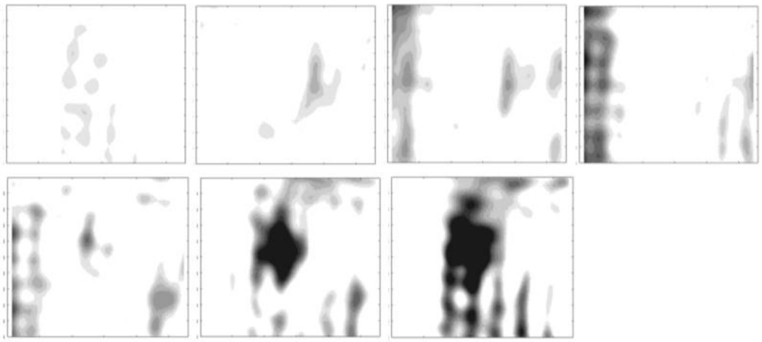

Figure 6: Scan results as horizontal cutting planes in depths from 2 mm to 14 mm (arranged from top left to bottom right) in distances of 2 mm.

These data also allow for the display as horizontal cutting planes through the device. Fig. 6 shows such planes for depths *z* from 2 mm to 14 mm with distances of 2 mm. The cutting planes at 6 mm, 8mm, and 10 mm near to the left edge of the scan show the strip-type resin enrichments. The cutting planes at 12 mm and 14 mm in their center show the 2 mm deep flat bottom holes, however not accurately in shape.

Some details have to be mentioned which have been used in the application of the described procedure:

- The above mentioned zeroing was done line-by-line.
- For better clarity of the display of the result, weak signals, i.e. originating from noise, were suppressed. This was done by only displaying indications beyond a certain threshold.
- The transfer function as shown above is only valid for infinitesimally small antennas in their far field. Practical antennas have a nonzero spatial extent. Their

amplitude characteristic in the near field can deviate from the above described *1/d* characteristic. Therefore in practical cases the transfer function is to be changed accordingly. In the present case a dielectric open ended rectangular waveguide was used as the antenna. And the amplitude characteristic was changed from *1/d* to *1/(d+b)*, with *b* being the narrow wall dimension of the used waveguide.

Conclusion

The shown evaluation procedure for microwave testing results in cross sectional and horizontal plane views of the defect distributions. The advantage of this procedure primarily is that it needs only a single test frequency. That allows the use of frequencies within the narrow ISM frequency bands, i.e. at 2.4 GHz, 5.8 GHz, and 24 GHz, for which normally no special licensing is necessary. Also microwave technic with a single frequency is simpler and therefore less expensive than the broadband FMCW technic. Furthermore this technic allows the use of relative low frequencies which is also less expensive than that for higher frequencies. In fact, the use of sufficiently low frequencies is necessary in order to have no ambiguity in the depth determination. This is especially the case of metal defects and defects with a permittivity larger that the surrounding.