MOISTURE DETERMINATION OF SOLID MATERIALS BY MEANS OF ULTRA-WIDEBAND RADAR AND TIME-FREQUENCY SIGNAL REPRESENTATIONS

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SUMMARY

This article deals with the determination of moisture content in materials. Since microwave methods (MM) meet the requirements of industry in the best way only these methods are addressed here. MM provide information about the relative electrical permittivity (REP) of material-water mixture in order to determine moisture content. They take advantage of the high REP of the water present in material. Current MMs work usually in narrow bandwidth and therefore acquire not enough information to determine moisture without calibration diagrams. In order to overcome this drawback this article proposes to apply ultra-wideband (UWB) radar.

The captured signals are usually processed in time or in frequency domain. However, nor time nor frequency domain is capable to suitable illustrate frequency dependence of the REP, that is used in MMs to determine the moisture. In all narrowband MMs, the frequency dependence of the water REP is neglected. This article proposes to reveal this information from measured data and use this additional information to help to solve the problem of moisture determination. In order to describe this information a time-frequency signal representation (TFSR) is applied.

Keywords: *microwave methods, ultra-wideband radar, time-frequency signal representations, moisture.*

1. INDRODUCTION

Moisture is in many cases a quality criterion for solid and liquid substances in industry. Moreover, it is required by ISO 9000 quality standards. Up to date, there were developed different moisture measurement methods for various materials, in order to insure their quality, reduce losses in trade and storage, save energy, reduce pollution of the environment. However, in many cases its accurate determination is still a big problem especially with respect to industrial requirements of in-situ measurement methods.

The determination of the water content may be based on different approaches. Each of them possesses its own advantages and disadvantages. However, for the industrial purposes only these methods are convenient that apply a high flexibility and easy handling as well as which do not influence (or destroy) the material under test (MUT) and which work continuously. Under these constrains, the moisture measurement by the MMs are the preferred ones.

MMs belong to the indirect procedures. More detailed information on the MMs state of art can be found in [1], [4], [5], [6]. The idea behind these methods is to take advantage of the high REP of the water. The measurement results are subjected also by several water independent influences – salt content, material density, random scattering by inhomogenity, etc. that make the moisture determination more difficult. Classical MM-systems apply a narrow band approach. Though this simplifies the equipment and coincides with the limitation by law of adequate frequency bands, it also strongly limits the performance of the sensors. By pressure of the industry, the rules for the use of UWB-systems are revised namely by the FCC (Federal Communications Commission of the US) and the Working Group FM of the European Radio Office. Thus, new device conceptions are under investigation applying UWB-excitation. Currently, short impulses or stepped/sweeped sine waves are mostly used for that purpose. But any other UWB-measurement conception may also be applied. By applying the radar principle, the goal is pursued to discover a spatial distribution of the moisture distribution in a body under investigation via the propagation behavior of the sounding waves.

UWB methods cover two classical approaches of data interpretation. These are:

1. determination of the frequency dependence of the MUT electrical properties (frequency domain approach [1]) and
2. analysis of the pulsed electromagnetic waves propagation (time domain approach usually referred to as time domain reflectometry [1]).

But unfortunately, these two approaches will not embrace the actual situation since both frequency depended material properties and spatial material distribution reflects in these two domains. Moreover, the different effects are hardly to discriminate. Fortunately, TFSRs that describe signals in two-dimensional (2D) domain of time and frequency can help to solve this problem. Since signal description in joint time-frequency domain has two degrees of freedom, it is expected that it should provide more information than signal description in separated time, or frequency domain. With regard to this fact it can be supposed that the proposed method of moisture determination using UWB radar measurements and TFSRs should provide more accurate results, or should need less information from a calibration diagrams.

2. TIME FREQUENCY SIGNAL REPRESENTATION

The most well known TFSRs are the Wigner distribution (WD) and the short-time Fourier transform (STFT) [2]. Although these TFSRs are the most frequently discussed TFSRs they cover only a small part of all developed TFSRs. At the present time, two important groups of the TFSRs are discussed [3]. These are the linear and the quadratic ones.

The linear TFSRs are defined by a linear transformation of the signals to be processed. STFT can be given as the most important example of the linear TFRs.

Because of better time-frequency resolution, the quadratic TFSRs are used more frequently than the linear ones. The WD [7], [11] is the most well known quadratic TFSR. The WD features the best resolution in time-frequency domain from all TFSRs. However, it is connected also with interference terms, frequently referred to as cross-terms that make its interpretation very difficult or sometimes impossible. Achievement of a reasonably small amount of the cross-terms all together with good time-frequency resolution is the most frequently discussed problem concerning TFSRs.

TFSRs are usually used for analyses of non-stationary signals. But here we are dealing with linear time invariant systems those behavior is considered as stable during measurement time. Such systems are completely described by either their frequency response function (FRF) or by the impulse response function (IRF). Both functions contain the same information about the system under test since they can be mutually transformed by Fourier transform. There is no gain of information by transforming data from time to frequency or vice versa. Since all accessible information is stored in FRF (or IRF), why should there be introduced an another representation? The answer is simply given by better possibilities of feature extraction and suppression of perturbation effects. The time domain is to be preferred to consider the geometrical aspects in connection with the wave propagation, whereas frequency domain is of advantage to analyze relaxation processes within MUTs. But in case of moisture measurements both effects cannot be separated. Thus, it is often difficult to interpret measured data by classical approaches. However, by joining time and frequency domain representations it is possible to find a middle course in order to overcome these inconveniences. The next chapters shall give an impression of the background and the first results of the new approach.

3. TFSR OF HOMOGENOUS MOISTURE MATERIAL

Firstly, an idealized example of the signal propagating through the moisture material will be given. It will be assumed that signal transmitted by means of radar is an ideal short time impulse (Dirac impulse) which frequency content is unlimited. Then, there will be considered infinitely expanded layer of material under test (MUT) covered from opposite side to the radar position by metal that reflects transmitted waves back to the radar. In order to simplify this example multiple reflections will be neglected. Most of the dry MUTs dispose of the frequency independent REP. Thus, the signal backscattered from the metallic backside produces in the joint time-frequency domain a line parallel to frequency axis shifted in time by the delay which the wave needs to propagate through the MUT and back. It means that all frequency components are underlying the same attenuation and phase- (respectively group-) velocity.

However, if some amount of water is added into the MUT its REP will be affected by the REP of water, which is frequency dependent and can be mathematically expressed as [5]

$$\varepsilon_{rH2O}(f) = \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1 + j2\pi f\tau}, \tag{1}$$

where f stands for frequency, ε_∞ is the limit of REP for infinity frequency , ε_s abbreviates the static REP of water and τ stands for the relaxation time of the water molecules. Since the water REP is frequency dependent, the behavior of the moist material will be also frequency dependent. All MMs benefit from this behavior. If a pulsed wave propagates through material containing moisture, the frequency dependence of the medium REP results in a smearing of its shape due to the variations of the attenuation $L(f)$ and phase velocity $v(f)$. Phase velocity can be expressed as

$$v(f) = \frac{1}{\sqrt{\mu RE\left[\varepsilon_{rMUT}(f)\right]\varepsilon_0}}, \tag{2}$$

where $RE[\varepsilon_{rMUT}(f)]$ is real part of the frequency dependant REP of MUT, ε_0 is absolute electric permittivity of free space and μ represents magnetic susceptibility of MUT.

The frequency dependent attenuation can be described by the following equation

$$L(f) = e^{-D\,2\pi f\sqrt{\mu\, IM\left[\varepsilon_{rMUT}(f)\right]\varepsilon_0}}, \tag{3}$$

where *D* represents the length of the wave trajectory in MUT and $IM[\varepsilon_{rMUT}(f)]$ is imaginary part of the frequency dependant REP of MUT.

The resulting REP of a material mixture depends on several factors of physical bounds. It is difficult to calculate it, but the value can be found always within the bounds indicted by two models mathematically described as [5]

$$\varepsilon_{rMUT}(f)=V_1\varepsilon_{rM}+V_2\varepsilon_{rH2O}(f) \qquad (4)$$

$$\frac{1}{\varepsilon_{rMUT}(f)}=\frac{V_1}{\varepsilon_{rM}}+\frac{V_2}{\varepsilon_{rH2O}(f)} \qquad (5)$$

where $\varepsilon_{rMUT}(f)$ is the REP of the dispersive medium created as the mixture of non-dispersive medium and water. V_1 and ε_{rM} represent the amount and the REP of zero humidity material contained in dispersive medium. V_2 and $\varepsilon_{rH2O}(f)$ represent the amount and the REP of water contained in dispersive MUT.

Consider a 20 cm thick material layer in order to illustrate typical appearance of the TFSR of dispersive media like a moist substance. The REP of the basic material ε_{rM} is frequency independent and equal to 5. The total REP of the moist substance is supposed to behave according the equation (4).

The ideal TFSR of signal that propagated through the MUT in which the amount of water was 11% is illustrated in Fig. 1. In the joint time-frequency domain it is possible to recognize three influences of the MUT moisture on parameters of the received signal. These are: propagation time, frequency and attenuation. It is easy to observe frequency dependence of phase velocity (higher frequency components propagate faster than lower ones). Simultaneously it is possible to see the frequency dependence of the attenuation of different frequency components (higher frequency components are more attenuated than the lower ones).

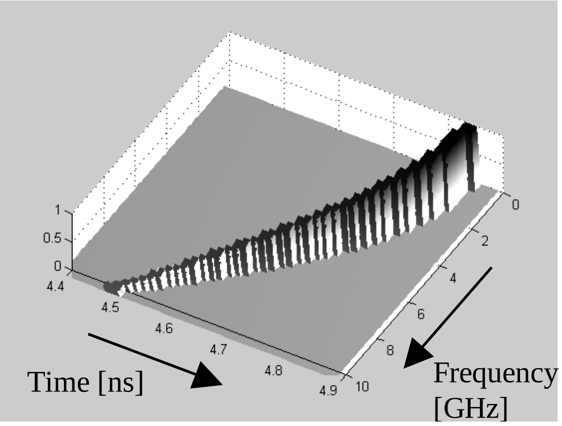

Fig. 1 Signal description in joint time-frequency domain (moisture - 11%)

The comparison of the influence of MUT moisture on signal features is presented in the Fig. 2. Here, the MUT moisture is presented as a parameter that changed from 0.1% to 11% with the 0.1% step. It is possible to recognize following facts:

1. the higher is the moisture the slower is the propagation of the transmitted signal through the MUT (e.g. for the 0.1% moisture signal arrives after 3.2ns and for the 11% moisture signal arrives after 4.8ns),
2. the higher is the moisture the more dependant is the phase velocity of frequency signal components (e.g. for the 0.1% moisture the phase velocity is almost frequency independent, however, for the 11% moisture the lower frequency components arrive approximately 0.1ns later than the higher ones),
3. the higher is the moisture the higher is the attenuation of higher signal frequency components (if the attenuation of –100dB is assumed to be the limit of the radar to acquire signal then in case of 0.4% moisture the radar is still capable to measure signal frequency components up to 8GHz, however, in case of 11% moisture the highest acquired frequency component is approximately about 5GHz).

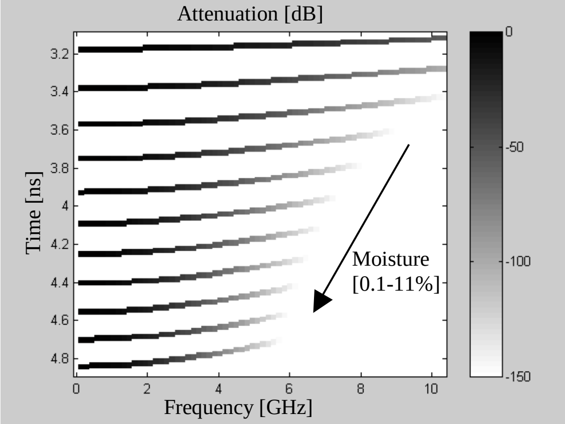

Fig. 2 Signal description in joint time-frequency domain

With regard to the above given figures, in order to produce similar TFSRs by real measurement it is necessary to apply UWB radar. The more limited is the radar bandwidth the less information is obtained from the measurement and the more difficult would be the moisture determination. The requirement of UWB radar is also necessary in order to resolve the dispersion in time-frequency domain (to distinguish among different phase velocities for different frequency components).

The following chapter gives very short overview of various UWB measurement principles.

4. UWB MEASUREMENT PRINCIPLES

There are three basic measurement principles that are mainly distinguished by the kind of applied stimulus signal:

Impulse technique - The impulse technique uses very short pulses. Impulse measurement systems are of very simple construction as long as the bandwidth does not exceed one or two GHz. The mean energy of a pulse is very low even for relative high amplitudes and the noise bandwidth of the sampling gates is very large. Thus, measurement method is sensitive to random noise.

Sine Wave Technique - This technique applies stepped sine-wave source and a heterodyn vector receiver. Devices applying this technique are usually referred to as network analyzers. They are very flexible laboratory devices but not suitable for practical purposes due to their cost, size, handling and relative big amount of time necessary to finish one measurement sweep. This may provoke problems in connection with a fast moving MUT (bulk material on a conveyor belt) or if the sensor shall scan an area.

Correlation Technique - From the theoretical standpoint, the correlation technique is the most flexible method of system identification since it is not fixed to a certain kind of test signal. The consequence is, that wideband stimulus signals may be applied that have a high (mean) power but a low peak voltages (compared to an impulse for example). The sensibility and the speed of the measurement system profits from the high (mean) power and the wide bandwidth of the signal - a design rule which is applied in all measurement systems.

The actual sensor elements are either UWB antennas or wave guides surrounded by the MUT. The measurement values refers either to a reflective or/and a transmission behavior of the sounding waves.

5. EXPERIMENTAL RESULTS

The phenomenon of the pulsed electro-magnetic wave smearing due to the moisture contained in MUT may not be observed in the time nor in the frequency domain separately. However, as mentioned above the joint time-frequency domain approach using an appropriate TFSR opens new possibilities. Previous chapters addressed this problem applying ideal TFSR, ideal transmitted signal and simplified MUT. However, the reality is much more complicated. We can use only a radar device whose bandwidth is constrained and the REP εr_{MUT} of the dispersive MUT is not influenced only by moisture contained in it but also by different MUT features such as its density, thickness, temperature, soil content and others. It means that all this MUT features influence the measured IRF (or FRF) of the whole system in different specific ways. Since only the moisture content influence is important to us it is necessary to separate this information from measured data. Up to date, the majority of presented solutions to this problem work only in small frequency bandwidth. Thus, the transfer function of the whole system is known only partially and impulse response function is unknown. This results in the necessity of information from calibration curves.

In order to improve the methods of moisture determination this article proposes to scan MUT by means of UWB radar and so obtain as much information about MUT as possible. Moreover, it is proposed to transform acquired signal into the joint time-frequency domain. It was shown that in this domain it is possible to observe MUT dispersivity all together with signal attenuation. Moreover, it is possible to handle these phenomena separately, what can significantly help to separate other MUT feature influences from the moisture influence.

In order to verify these theoretical assumptions an experimental measurement was performed. A network analyzer working up to 6GHz [12] was used for the measurement. A dual L-Wigner distribution (DLWD) [8], [9], [10], [13], which provides reasonably good time-frequency resolution without the large amount of the disturbing interference-terms, was chosen to transform the measured signals into time-frequency domain.

A reflection measurement constellation was used for the measurements. The probe antennas were situated above a plastic box filled with sand and placed on metal folia (Fig. 3), which reflects the transmitted electromagnetic waves back to the radar. The antennas were moved above the plastic box along a line crossing this box. The measurements represent a 2D data set (so called B-scan or Radargram). A B-scan is formed by stacked A-scans that are nothing but IRFs at different locations. One direction of the B-scan is related to the down-range and the second one to the cross-range. The result of the described measurement after the signal preprocessing is presented in Fig. 4. The reflection from the metal layer, multiple reflections from the metal layer and the reflection from the sand surface are clearly to be seen from the B-scan.

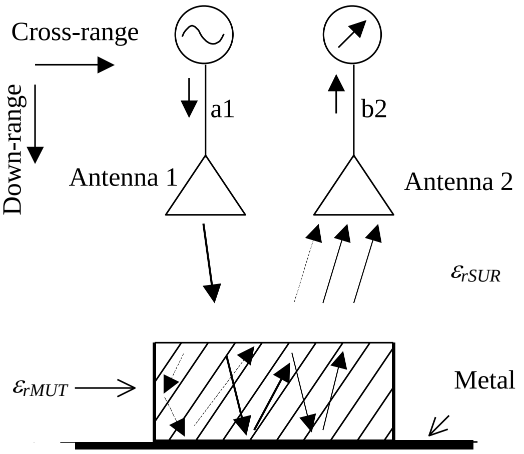

Fig. 3 Measurement constellation

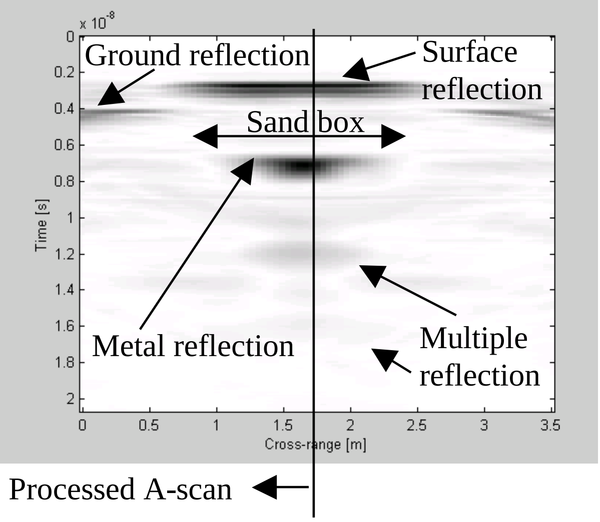

Fig. 4 Result of the measurement

There were performed 5 measurements of different degree of moisture (about 0%, 5%, 6.5%, 7.5% and 10%) in order to compare its influence.

In order to reveal information about the moisture stored in the measured data the preprocessed A-scan (one measurement in the down-range direction) was presented in time-frequency domain. Fig. 5 illustrates the DLWD of an A-scan from the central part of the B-scan.

The first impulse represents the scattering from the surface of MUT. Due to the fact that this scattered wave propagated though a non-dispersive medium (air) it is has the shape similar to the one of the Dirac impulse. Therefore, it is presented in time-frequency domain as a line parallel to the frequency axis occurring in the time of the arrival of the scattered impulse. Furthermore, it is possible to see that the second scattered wave is dispersive in consequence of the water influence. Thus, the high frequency signal components arrive sooner than the low frequency ones.

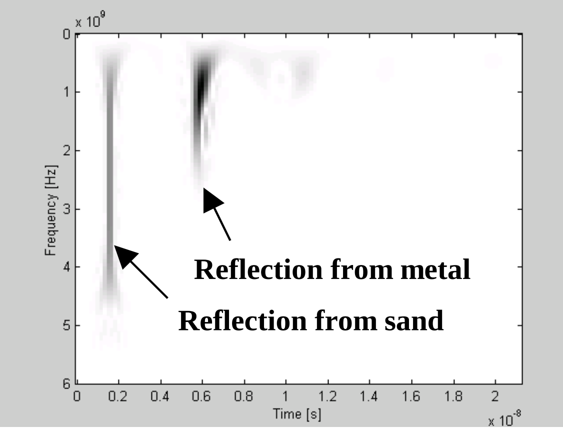

Fig. 5 TFR of measured signal

In the performed measurements of MUTs containing different moisture it was possible to observe that the difference between the propagation of higher and lower frequency signal components was becoming greater as the MUT moisture increased. In order to compare aforementioned fact, the curve characterizing time delay considering individual frequencies was linearized (Fig. 6) and the moisture dependence of the directivity of linearized curves computed according the following equation

$$k(F) = \frac{\left(f2(F) - f1(F)\right)1e9}{\left(t2(F) - t1(F)\right) f_s}$$

is displayed in the Fig. 7.

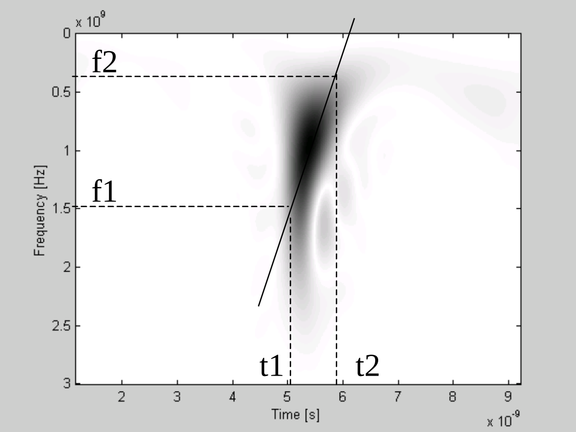

Fig. 6 Computation of the directivity

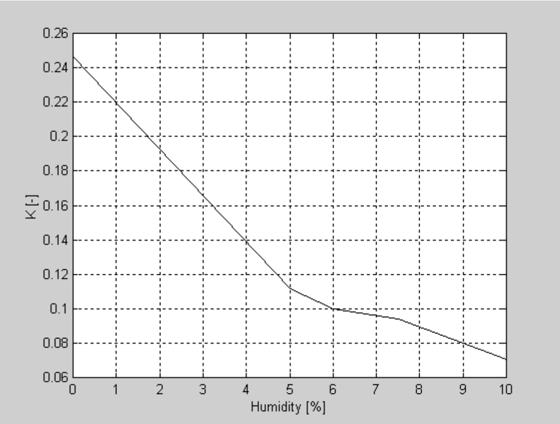

Fig. 7 Directivity as a function of moisture

6. CONCLUSION

Here, it was presented how could the description of the dispersive medium in time-frequency domain be conveniently used for the moisture determination. It was shown that TFSR of measured signal containing information about dispersive medium provides more information than signal representation only in time or in frequency domain. Thus, it is supposed that the proposed approach will possesses following advantages over other microwave approaches:

1. perform more precise moisture determination,

2. provide moisture measurements less sensitive to MUT characteristics (density, temperature, soil content and others),
3. need less information from calibration diagrams.

Presented new approach for dispersive medium feature extraction in time-frequency domain can be suitable for the determination of the material moisture by means of UWB radar and TFSRs. It is supposed that this approach can replace determination of the material moisture in time domain or in frequency domain. However, this must be verified by extended research analyzing a number of measured signals.

Since in nature there exist wide variety of phenomena featuring dispersive character the proposed method applying TFSRs is not useful only concerning moisture determination, however, this method can be of great advantage analyzing other dispersive phenomena.

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BIOGRAPHY

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Jürgen SACHS was born on 15.01.1953. He received his Dipl.-Ing. degree in Electrical Engineering in 1975 and his PhD in 1980 from the Technische Universität Ilmenau. From 1982 to 1985, he was lecturer at the Institut Nationale d’Electronique de Sétif, Algéria. He joint the Technische Universität Ilmenau Faculty of Electrical Engineering and Information Technology in 1985. He gives lectures in general electrical measurement technology, RF-measurements and Radar technology. His research interests include RF-measurement technology and signal processing. Currently, he is co-ordinator of two European projects for humanitarian demining by use of high resolution radar (surface penetrating radar).