Permittivity Measurements with a Resonant Cavity to Develop Human Tissue Phantoms for Microwave Imaging

Nikola Petrovic(1), **Magnus Otterskog**(1)

(1)School of Innovation, design and engineering, Mälardalen University,
Box 883, 721 23 Västerås, Sweden

nikola.petrovic@mdh.se
magnus.otterskog@mdh.se

ABSTRACT

In order to create human tissue phantoms for a microwave imaging system, a method to determine the complex permittivity is needed. For this reason a cavity perturbation method has been analyzed and used to perform measurements characterizing the complex permittivity of different fluid mixtures. Results show good agreement on single frequency between the measurement with the reentrant cavity and references. However the complex part of the final material mixture mimicking human tissue are higher than expected, which makes 1.2-propylene glycol inappropriate as a human tissue phantom material. The cavity perturbation method is still a suitable method for measuring liquids and with more work it might even be reliable for gel-based materials.

1 INTRODUCTION

Microwave imaging for medical applications is of big interest nowadays. The imaging with microwaves allows nondestructive evaluation of biological tissues. Changes in the dielectric properties of tissue can be related to their physiological condition. The contrast in permittivity for different in-vivo tissues (fat, bone, malign tumor, vascular tissue etc.) is higher for microwaves than the most successful tool used today X-ray Computed Tomography (CT) is able to produce. However, microwave imaging techniques, needs a lot of improvement in both hardware (antenna, electromechanical parts and RF-design) and in the software (imaging algorithms) to be considered as a reliable modality for biomedical applications. There has been proposed several applications of microwave imaging in the biomedical field and one of them is using microwaves for breast tumor detection as an alternative mammography [1]. The characterization of dielectric properties of human tissue then becomes very important in the microwave region.

Phantoms that mimic human tissues have been of great importance for the development and testing of different medical imaging modalities. Our motivation with this work is realization of human tissue phantoms for our recently designed and validated new flexible robot controlled microwave imaging system at Mälardalen University (MDH) [2].

There has been a number of resonance methods developed for measuring the dielectric properties of materials in the last decades [3]. Methods for measuring the complex permittivity of lossy liquids at microwave frequencies are especially interesting because lossy dielectric liquids can match the permittivity of biological tissues very well. A widely used technique to determine the complex permittivity, the dielectric constant and loss factor, is the resonant cavity perturbation method. The sample to be studied is introduced into a cylindrical resonant cavity in a suitable way and its complex permittivity is determined from the shift of the resonant frequency and the change of the cavity quality factor (Q-factor). The advantage with the cylindrical cavity in comparison to rectangular cavities is that it offers higher Q-factor and therefore higher accuracy.

Herein a so called reentrant cavity is presented able to measure dielectric properties of different fluids for breast phantom development to our microwave imaging system.

2 CAVITY PERTUBATION THEORY

The permittivity can be calculated from the well known perturbation theory equations if the measured sample is homogenous and much smaller than the cavity [4]. Perturbations in the complex permittivity of all parts of the material in a resonant cavity will change the resonance frequency and Q-factor. Thus by measuring the change in resonance frequency and the change in Q-factor the dielectric change can be calculated. The complex permittivity $\varepsilon^* = \varepsilon r' - j\varepsilon r''$ can be obtained with the following equations:

$$\varepsilon_r^{'} = 1 + \frac{2}{C}\left(\frac{f_1 - f_2}{f_2}\right) \tag{1}$$

$$\varepsilon_r^{''} = \frac{1}{C}\left(\frac{1}{Q_2} - \frac{1}{Q_1}\right), \tag{2}$$

where f and Q are the resonant frequencies and the Q-factor of the cavity, respectively. The subscripts 1 and 2 refer, respectively, to the cavity without the sample and after the introduction of the sample into the cavity. The coefficient C is representing

$$C = \frac{\iiint_{V_S} E_1 \cdot E_2 \, dV}{\iiint_{V_C} |E_1|^2 \, dV} \tag{3}$$

E_1 and E_2 are the microwave electric fields in the cavity before and after the introduction of the sample. V_c is the volume of the cavity while V_s is the volume of the sample. For permittivity measurements with the cavity perturbation method, the parameter C is assumed to be constant, independent of the permittivity of the sample. However, in (3), the perturbed field in the sample E_2 is related to the permittivity, shape and size of the sample, so C changes for each measurement [5]. Using two parameters A and B instead of C in (1) and (2) [5] more accurate measurement results are obtained as follows:

$$\frac{f_1 - f_2}{f_2} = A(\varepsilon_r^{'} - 1)\frac{V_s}{V_c} \tag{4}$$

$$\frac{1}{Q_2} - \frac{1}{Q_1} = B\varepsilon_r^{''}\frac{V_s}{V_c} \tag{5}$$

Parameters A and B are functions of the geometry and the working mode of the cavity, but also the permittivity and volume of the sample. As it is very complicated to calculate parameters A and B analytically, the parameters A and B are acquired through calibration. The calibration is performed using a sample of known permittivity with similar properties as the sample being measured.

Assuming that the electrical field is tangential to the surface of the sample, the electrical field inside the sample equals the external field [6], which gives the case in (4)($\varepsilon_r^{'}$-1). The assumption regards also using a thin sample.

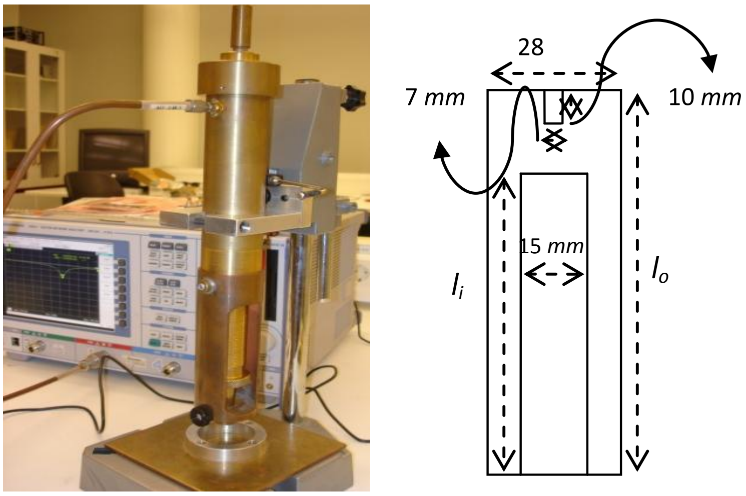
3 EXPERIMENTAL SETUP

3.1 Determination of Resonance Frequency and Q-factor

The complex permittivity is calculated in terms of resonant frequency and the Q-factor, as mentioned in the previous section, of the resonant cavity with and without the sample. The accuracy of the complex permittivity is therefore dependent on the accuracy of the measured resonant frequency. A vector network analyzer (VNA) from Rhode and Schwarz model ZVB-8 was used to measure the scattering parameters with a frequency resolution of less than 1 kHz. For calculating the Q-factor a well known method is used were the 3dB bandwidth is defined from the measured scattering parameters (S-parameters). However for a more accurate measurement of high conductivity samples other methods are suggested in literature [7] and [8]. The measured frequency and calculated Q-factor are then used in (4) and (5) to determine the complex permittivity of the sample.

3.2 Measurement Setup

The cavity is a so called reentrant cavity and is depicted in Fig. 1a. The sample holder is made out of quartz and the sample can be exchanged from the outside of the cavity. The cavity is made out of brass (copper-zinc alloy). Measurement from ~2 to ~7 GHz can be performed with the cavity, however in this paper only a single frequency has been used. The length of the outer, l_o, and inner conductor, l_i, can be changed independently from each other, Fig. 1b, to obtain resonance at a proper frequency.



a) *b)*

Figure 1: *The cavity setup (a), cross section of the inner dimensions of the cavity (b).*

In the measurements with the reentrant cavity, a sample of volume 0.5ml was used. This volume is considered small enough so that no changes in resonance frequency or Q-factor can be observed if the volume is decreased to 0.4ml or increased to more than 0.5ml. Thus all of the electric fields were contained inside the cavity or in the sample. Therefore a variation in the volume will not cause a perturbation of the cavity, as long as the volume stays above 0.4ml. All volumes were measured to an accuracy of below 1%, so there is no volume effect on the resonance frequency measurements.

In order to study dielectric properties of materials mimicking biological tissues a feasibility study of the resonant cavity was done measuring properties of 1.2-propylene glycol and water mixtures. In table 1 three series are presented on the empty sample holder and the sample holder filled with water or 1.2-propylene glycol. In each measurement series 10 measurement was conducted and the resonance frequency can be determined with a repeatability of about 18-35 kHz, while the Q-factor can be obtained with a precision of 4-7 units. The conclusion is that the repeatability of the cavity is considerably worse than the measurement inaccuracy of the instrument (VNA).

Table 1: *Resonance frequencies and Q-factors of measurements on cavity loaded with water, 1.2propylene glycol and with empty sample holder.*

	Resonance frequency		Quality factor	
	Mean [GHz]	Standard deviation [kHz]	Mean	Standard deviation
Empty	3.600502	18	834	6.5
Water	3.597753	25	714	4.2
1.2 propylene glycol	3.599250	35	590	3.7

The resonance frequencies of measurement on different mixtures are presented in Fig. 2. The resonance frequency change is not a linear function of the volume fraction, which means that one of the approximations doesn't necessarily hold when the dielectric properties of the sample undergo large changes. However for the moment this fact has been disregarded in the initial study of the cavity.

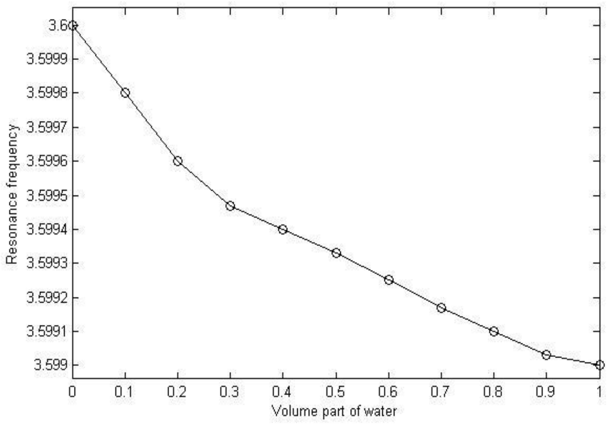


Figure 2: *Resonance frequency of water and propylene glycol mixtures at room temperature.*

If the problem is considered to be linear and by comparing the average resonance frequency shift with the average permittivity change a rough estimate of the permittivity resolution can be calculated. When the sample mixture is changed from pure 1.2-propylene glycol to pure water the real part of the complex permittivity undergo a change of approximately 71 units and the resonance frequency change 1 MHz. As a result, a change of 1 kHz in resonance frequency on average matches 0.057 units. However the repeatability of the measurement system is limited to approximately 35 kHz so only a permittivity difference of ~2 units can be identified. The real tissue permittivity value varies a lot in-between individuals and therefore the accuracy of 2 units is good enough for the initial study.

3.3 Permittivity measurements and results

A feasibility study of the resonant cavity was done measuring the dielectric properties of materials mimicking human tissue. The first experiments were conducted using water with different salinity. Measurements were also preformed on 1.2-propylen glycol with different solutions of water and salt simulating human tissues and finally on human blood sample. Some of the measurement results are shown in table 2 and compared with references. The outer conductor is set to l_o=81*mm* and the inner l_i=57*mm* during the measurements (see Fig. 1b).

__Table 2a__: Measured values preformed @ 3.6 GHz and a temperature of ~21.5°C

	Distilled water ε_r''	Saline water 0.5% NaCl ε_r''	Saline water 1% NaCl ε_r''	Saline water 1.5% NaCl ε_r''
Resonant Cavity	15	17.8	21.2	25
Stogryn [4]	14.6	18.3	21.7	25.2

__Table 2b__: Measured values preformed @ 3.6 GHz and a temperature of ~21.5°C

	1.2-propylen glycol	Tissue phantom 50%-50% (*)	Human blod sample
Resonant Cavity	ε_r'=6 ε_r''=4	ε_r'=24 ε_r''=19	ε_r'=70 ε_r''=12
Coaxial probe	ε_r'=6.25 ε_r''=3.9	ε_r'=25.5 ε_r''=20	ε_r'=68 ε_r''=14

*Solutions of 50% distilled water and 50% 1.2-propylen glycol

One of the purposes with the microwave imaging system constructed at MDH is to investigate the possibility of detecting early stage breast tumors with quantitative images. For this purpose a breast phantom was created by using a 3mm thick Plexiglas (ε'=2.73, ε''=0.01) cylindrical structure, see Fig. 3, with a diameter of 100mm filled with a solution of 50% distilled water and 50% 1.2-propylene glycol simulating an average of three different breast tissue groups. Gelatin based materials are preferred due to their stable mechanical properties so agar was added to the solution to obtain such kind of material. Different 2mm thick Plexiglas tubes are placed inside the Plexiglas cylinder in order to simulate tumors of size between 10 to 16mm in diameter and were filled with a solution of 90% water, 10% 1.2-propylene glycol and salt simulating the tumor tissue. The desired values of the complex permittivity are those given in table 3 [1], [9] and [10]. Note that they come from a good compromise between measured values on existing phantoms materials and those found in the literature.

***Table 3**: Complex permittivity used for developing the breast tissue phantom*

Materials	ε_r'	ε_r''
Breast tissue	35	5
Tumor	65	14
Skin	37	8
Water	77.5	8.65

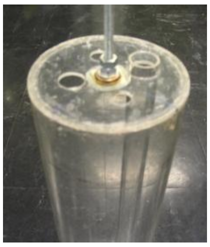


***Figure 3:** The cylindrical breast phantom*

Measurements and imaging reconstructions were performed on the phantom, with the planar microwave imaging system at Supélec in Paris, which showed an incorrect value of the imaginary part of the complex permittivity. That is a consequence of a chemical reaction when mixing 1.2-propylene glycol with water. Air bubbles was also a problem when the gel based phantom material reached room temperature. Currently we are using triton X-100 and water mixtures for creating our narrow banded phantoms and at this point it is clear that mixture is suitable for our breast phantoms.

4 CONCLUSION

The perturbations in a resonant cavity (reentrant cavity Fig. 1) prove to be a promising method for permittivity measurement of materials mimicking human tissue. However, there has to be some improvements to make the method more reliable and more general. Explicitly there has to be a technique of measuring other materials than fluids with satisfying results.

Another problem that arises is the instability of the reentrant cavity. During the measurement there have been problems with the gaskets in the cavity between the inner and outer conductor and between the outer conductor and the outer casing of the cavity. That has caused problems during the measurement and is a source of error.

Regarding the phantom materials, 1.2-propylen glycol and water has proved to create a material with high losses when mixed. This makes the 1.2-propylen glycol inappropriate to use as a breast phantom material. Triton X-100 and water mixture are used at the present as breast phantom materials and initial studies have shown promising results.

A future step is to improve the stability and the other points mentioned above. Also simulations of the cavity would be interesting in the future to see how well the measured and simulated data correlate. Future work will also be concerned with the characterization of the image reconstruction capabilities of the MDH system using the developed breast phantoms. The complex permittivity distribution of the object will be computed with an inverse scattering problem solver based on a Newton-Kantorovitch iterative method using multi incidence set of data obtained from the robot based acquisition system.

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