Calibration of Biomedical Dielectric Sensors Optimised using Genetic Algorithm

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Abstract

Biomedical sensors using the resonant cavity perturbation (RCP) technique can measure the dielectric properties of tissues from the changes to resonant frequencies and their Q-factors. However they are difficult to calibrate for irregular sample geometries. We extended the RCP equations by including higher-order terms, and used a genetic algorithm to optimise the complex parameters. Applied to a flat cavity resonator and to a current sheet sensor, this approach gives excellent agreement between the predicted and literature values for reference liquids in the first case and good agreement in the second. Two-dimensional mappings of the sensor responses are presented.

1. Introduction

Dielectric measurements in medicine give useful clinical information by distinguishing between healthy and tumour tissue for diagnosing and assessing cancer [1] and by assessing abnormal hydration in oedema, inflammation and kidney disease and in nutritional studies [2].

The resonant cavity perturbation (RCP) method [3] of measuring the dielectric properties is a long established technique in which the permittivity and loss factor are calculated from the changes to the resonant frequency and Q-factor of a cavity when a sample is placed therein. It is ideally suited to precisely-machined geometries of samples such as ceramic resonators which are disc-shaped. For irregular geometries it becomes harder to calibrate but in principle this can still be done empirically from measurements on reference materials of known dielectric properties. The advantage over broad-band techniques such as the open-ended coaxial sensor is that only scalar measurements are needed. The use of a single frequency is not a drawback if the dielectric properties vary only slowly with frequency anyway, or if the application is for example dielectric heating at a single frequency [4].

Kraszewski and Nelson have used RCP to measure the moisture content of seeds and in other agricultural applications [5]. Medical applications include the measurements Land and Campbell made on pathology samples from breast biopsies at 3GHz [6], the novel resonant sensors of Johnson et al. for in-vivo detection of breast tumours [7], and the body water measurements of Robinson et al. at 60MHz [2].

In this paper we consider two biomedical sensors where it is difficult to apply RCP theory to the calibration owing to the 'open' nature of the resonator. These are (a) a flat resonant cavity where a cylindrical sample is inserted through holes on opposite sides, and (b) the current-sheet sensor in which the fields extend outwards into tissue when it is placed against the skin, and which can detect changes in the underlying tissues to a depth of several centimetres.

In both of these we have adapted the RCP equations by empirically adjusting the parameters and also adding higher-order terms to get the best fit to reference liquid data, using a genetic algorithm (GA). GA's are one form of evolutionary optimization where ideas from natural evolution are used. Evolutionary optimisation has recently experienced a remarkable growth; its applications covering a huge range of problems in a great many disciplines. In contrast to methods such as least squares, GA's can handle non-linear equations [8].

2. Theory

Complex permittivity is given by $\varepsilon^*=\varepsilon'-j\varepsilon''$ where ε', ε'' are respectively the dielectric constant and loss factor. Both real and imaginary parts of ε^* depend on tissue water content. The correlation improves with frequency as cell membranes become 'short circuited' and contribute less to the permittivity above tens of MHz [2]. Dielectric measurement can therefore distinguish between water and fat, or tumour and surrounding breast tissues.

RCP theory for a sample in a cavity [5] defines the complex frequency shift in terms of the change Δf of the resonant frequency f_0 and its Q-factor, and predicts that

$$\Delta\Omega = \frac{\Delta f}{f_0} + \frac{1}{2} j\Delta\left(\frac{1}{Q}\right) = -\frac{1}{2}\frac{1}{C}\frac{\varepsilon^* - 1}{\left[1 + A(\varepsilon^* - 1)\right]}\frac{v_s}{v_c} \qquad (1)$$

where C is a geometrical constant dependent on the position of the sample and v_s/v_c the ratio of sample volume to cavity volume. The 'depolarisation factor' A depends on the shape of the sample and is between zero and one.

Hence we can determine ε' and ε'' from Δf and $\Delta(1/Q)$ by comparing real and imaginary parts:

$$\varepsilon^* = 1 - \frac{\Delta\Omega}{A\Delta\Omega + k} \text{ where } k = \frac{1}{C}\frac{v_s}{v_c} \tag{2}$$

If the depolarisation factor A is zero (which only occurs for a thin cylinder or slab parallel to E-field) then the variables separate and ε' is a function of Δf, and ε'' is a function of $\Delta(1/Q)$. Otherwise we a get complex mapping of $\Delta\Omega$ to ε^*. This is the case for most of the geometries that will be encountered in biomedical applications.

3. Sensors

The geometry of the flat cavity is shown in fig. 1 (left). The holes are in both the lid and the base. Short monopole antennas attached to BNC connectors enable the resonant frequencies to be measured by connecting these to a network analyser. Samples in tubes are inserted into the holes in the cavity.

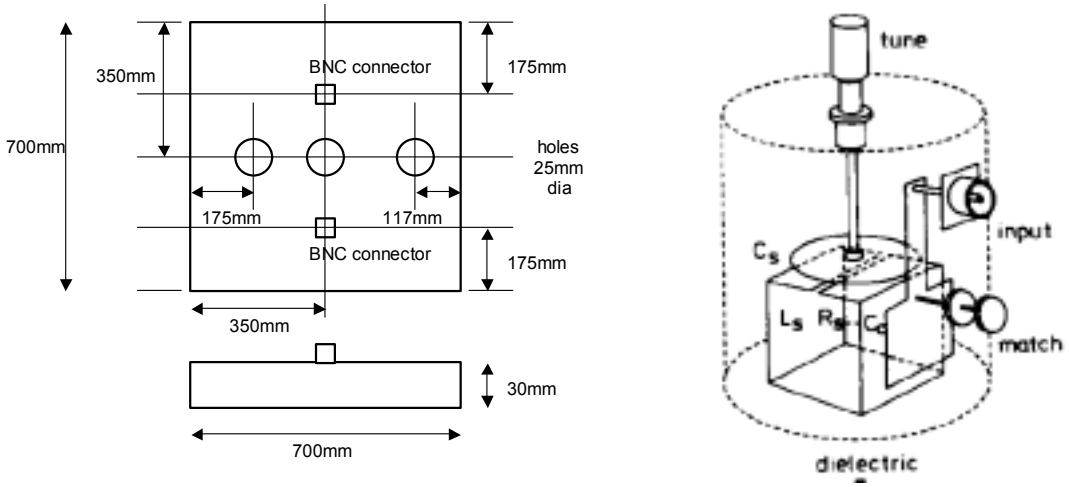

Figure 1: dielectric sensors. Left, flat cavity resonator with holes for samples. Right, current sheet sensor

The fundamental resonant frequency of a square cavity is given by $c_0/\sqrt{2}\ w$ where w is width, giving f_0 of 303MHz. The E-field is vertical. The sensitivity k should be proportional to the square of the electric field strength, which varies sinusoidally across the cavity. Three holes at distances of $w/6$, $w/4$ and $w/2$ from the edge give different sensitivities which should be in ratio 1:2:4. Measurements on reference liquids in bottles show that the fringing fields above and below holes do not significantly change the perturbation at distances greater than 15mm.

The cavity was calibrated with ten reference liquids whose properties are known (Table 1). The analytical values of the RCP parameters are A=0 and k=0.00148, but these give highly inaccurate values of ε^* for the reference liquids because the calculation does not include the fringing fields. We could try changing the parameters empirically but how should they be optimised?

The second device, the current sheet sensor, was developed in Bristol in the early 1990s by Johnson et al [7]. The sensor (fig. 1, right) is tuned to resonate in air at 500MHz. It gives point measurements of Δf and $\Delta(1/Q)$ which can form an image by raster scan over a region of body. This can show differences between breast tumour and healthy breast by comparing left and right images.

Johnson et al calibrated their sensor with reference liquids (table 2). They showed that numerical simulation with the finite difference time domain (FDTD) method could solve the 'reverse' problem of producing a complex mapping of ε^* to complex frequency shift. However the time needed per simulation makes an iterative approach unfeasible for an actual measurement of permittivity, and a faster method is needed.

Our approach was to extend equation (2) to include higher-order terms, and to optimise the calibration equation for the current-sheet sensor by empirically selecting coefficients for best fit to the reference data:

$$\varepsilon^* = 1 - \frac{\Delta\Omega + p(\Delta\Omega)^2}{k + A\Delta\Omega + q(\Delta\Omega)^2} \tag{3}$$

4. Genetic Algorithm

A genetic algorithm was used to optimise the functional fit to the data by allowing the parameters *p, k, A* and *q* to vary. Initially these parameters also had complex values but after initial trials it was found that better results were obtained by keeping them real. A floating point GA was used (as against a binary GA) since these generally perform better. A population size of 20 was chosen using a steady state algorithm, which is one in which not all of the population is replaced by offspring at each generation, but only a proportion of it. The proportion chosen was to reproduce 15 offspring from the population of 20 parents at each generation, because this proportion of offspring has worked well in previous work [9, 10]. Tournament selection was used to select the parents from the population, and arithmetic crossover was used with a probability of 0.8. Arithmetic crossover is where a random number $r \in$ [-0.5,1.5] is chosen and offspring are produced by the equation

$$c = r * p_1 + (1-r) * p_2 \tag{4}$$

where c is the offspring and p_1 and p_2 are the parents. The mutation rate is an important consideration since it is the only control in a GA to prevent the optimisation from getting stuck in a local optimum. Here we have used a mutation rate of 0.04, a value that has worked well in other optimisation problems [9, 10]. The cost function was chosen to be the sum of the squared relative differences between the functional fit and the actual data values, where the summation is over all data points.

The GA was run for around 16,000 generations, separately for first order and second order fits and for the two sets of data from the different sensors. The resulting best fit parameters are reported in the next section.

5. Results

For the flat cavity resonator, the first-order best fit for the central hole was A=0.0301352, k=0.00108646 (Table 1). For the other two holes, the sensitivity was reduced by approximately 0.5 and 0.25 respectively, as predicted. The second-order fit was not a great improvement, so is not shown. The agreement in ε^* is excellent except for two liquids (saline) where conductivity was highest. This appears to be due to the poor field penetration in these liquids. Skin depth d_p is shown in col. 3 of Table 1 – the fit is poor when $d_p <$ diameter of hole (25mm). Discounting saline of 18g/l and 27g/l, the rms difference in ε' is 1.1 and in ε'' it is 2.5.

Table 1: results for flat cavity resonator

liquid	temp. (°C)	d_p (mm)	$\Delta\Omega$ (measured)	ε^* (literature)	ε^* (calculated)
dimethyl sulphoxide	28	1590	-0.02033+0.0002648i	46.07-1.36i	43.9-1.28i
ethanediol	28	305	-0.01927+0.001587i	38.8-6.51i	38.5-6.68i
ethanol	28	296	-0.01424+0.002077i	22.5-5.13i	22.2-5.18i
methanol	28	758	-0.01761+0.0007136i	31.9-2.37i	32.6-2.50i
propan-1-ol	28	191	-0.01172+0.003412i	16.2-6.86i	16.0-6.76i
water	25	2540	-0.02508+0.0001237i	78.5-1.11i	76.8-1.23i
saline 4.5g/l	25	60.4	-0.02707+0.0043198i	77.0-48.2i	76.0-52.0i
saline 9g/l	25	33.6	-0.02938+0.005382i	75.5-93.7i	76.4-87.6i
saline 18g/l	25	20.4	-0.03388+0.005179i	72.7-180i	50.2-196i
saline 27g/l	25	15.9	-0.03417+0.003879i	70.1-262i	89.2-249i
(air)	25	∞	0	1	1

For the current sheet sensor, the second order equation gave a much better fit than the first order, with p=-96.7086, k=0.00083426, A=-0.0251352 and q=1.39936 (Table 2). The rms difference in ε' is 7.2 and in ε'' it is 3.7. These results are not as good as for the flat cavity. However it is still impressive that it works so well in a geometry so different from those in which RCP is traditionally applied, and in which the field patterns vary with ε^*.

Figure 2 shows 2-d mappings of ε^* to $\Delta\Omega$ for the two sensors. For the current sheet sensor, the calibration equation correctly predicts that the frequency shift is positive for large ε''.

6. Conclusion

By using the genetic algorithm to optimise the coefficients we are able to calibrate dielectric sensors even when there is 'awkward' sample geometry. This will extend the practicability of rapid dielectric measurements in biomedical applications.

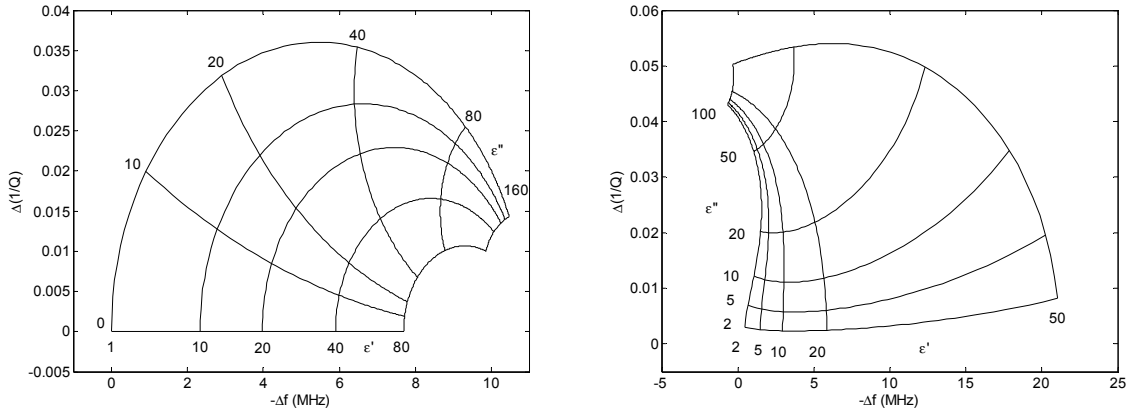

Figure 2: mapping of permittivity to complex frequency shift for flat cavity (left) and current sheet sensor (right).

Table 2: results for current sheet sensor

liquid	temperature (°C)	ε* (literature)	ε* (calculated)
cyclohexane	22.5	2.02-0.00i	2.14+0.27i
chloroform	22.5	5.10-0.12i	5.00+1.07i
acetone	22.5	21.3-0.25i	17.4-2.11i
butan-1-ol	22.5	6.84-6.20i	7.03-8.87i
propan-2-ol	22.5	9.50-7.89i	10.5-10.9i
ethanol	22.5	19.9-8.95i	17.0-10.0i
methanol	22.5	32.8-4.72i	23.7-8.25i
ethanediol	22.5	35.6-13.8i	26.6-15.2i
saline 5g/l	22.5	77.3-32.1i	64.6-37.7i
saline 9g/l	22.5	76.0-55.4i	62.6-53.9i
saline 29g/l	22.5	69.9-163i	76.0-172i
(air)	22.5	1	1

7. References

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