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KOSTADIN BRANDISKY
DOMINIK SANKOWSKI
ROBERT BANASIAK
Faculty of Electrical, Electronic, Computer and Control Engineering
Technical University of Lodz

OPTIMIZATION OF ECT SENSOR USING GENETIC ALGORITHM

Recenzent: **prof. Jan Sikora**

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In this paper the optimization process of 8-electrode cylindrical Electrical Capacitance Tomography sensor with two types of inter-electrode shields has been presented. The aim is to obtain maximum uniformity of the sensitivity maps of the sensor, while keeping the mutual capacitances between the electrodes above a predefined level. The optimization method used is a Genetic Algorithm. As results, optimum dimensions for the gap, shield, mounting pipe and insulation are found.

1. INTRODUCTION

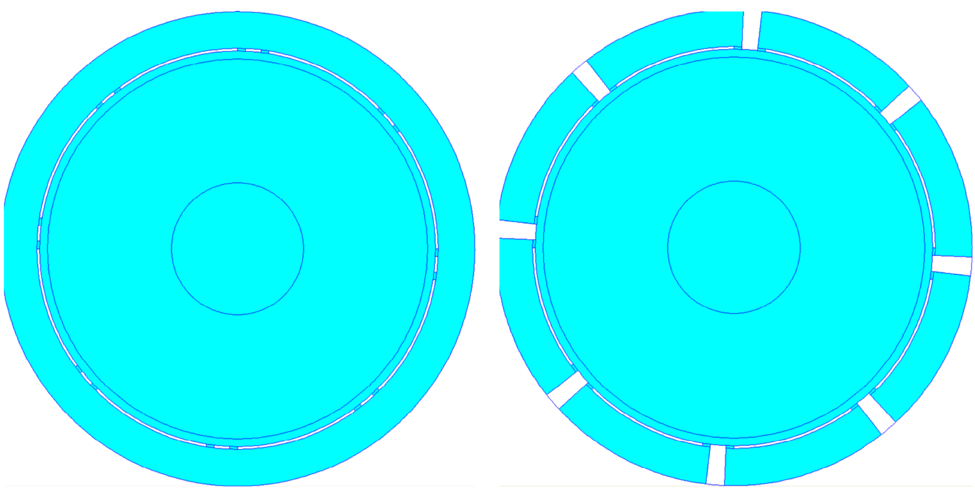
This paper considers the optimization of Electrical Capacitance Tomography (ECT) sensor. The aim is to obtain maximum uniformity of the sensitivity maps of the sensor, while keeping the mutual capacitances between the electrodes above a predefined level. The optimization variables are defined as geometric parameters of the sensors and permittivities of the materials. The optimization method that has been used is Genetic Algorithm (GA). As results, optimum dimensions for the gap, mounting pipe, shield and insulation can be determined, which ensure more uniform distribution of sensitivity maps in the sensing area.

2. OUTLINE OF THE PROBLEM

Electrical Capacitance Tomography is a fast and relatively cheap non-invasive imaging method that is intended to observe industrial processes in pipes and tanks, containing dielectric materials, such as gas-oil flows in pipelines or solid media flows in pipes or reservoirs. An ECT system measures mutual capacitance changes between pairs of electrodes distributed around the circumference of a pipe containing the multi-phase flow to be imaged. The permittivity distribution is then obtained using inverse problem solution, which gives an approximate image of the flow distribution in the pipe.

The sensor under study consists of 8 measurement electrodes over cylindrical surface /Fig. 1/. Between the electrodes there are grounded shields in the form of strips - Fig 1a and radial bars - Fig. 1b. The shields diminish the mutual capacitances between the adjacent electrodes and thus, the difference between the minimum and maximum mutual capacitances. This decreases the requirements to the input dynamic range of the measurement hardware.

The finite element method (FEM) has been used to simulate the electric field inside the computational model of ECT sensor in order to obtain sensitivity distributions. The sensitivity of an ECT system is an important characteristic, which depends upon the sensor geometry. As the capacitance values are very small, typically in the range of 0.01–1 pF [1,3], the dimensions of the electrodes must be suitably chosen to allow the mutual capacitances to fall inside the measurement range of the measurement system. Equal sensitivity of the sensing domain is essential to avoid an artifact or image distortion in the reconstruction result, due to poor uniformity of the sensitivity distribution. A fundamental goal of the ECT sensor design is to distribute the electrical field intensity uniformly all over the investigated volume [2,6,7].



a) b)

Fig. 1. Sensor geometry: a) strip shields; b) bar shields between electrodes

In the literature devoted to sensor design, usually one-parameter study is achieved, varying one parameter at a time. Such a study cannot take into consideration the interaction between the parameters and it cannot find a possible best-optimized design. The use of genetic algorithm [4] here allows to optimize the sensor by making its sensitivity as uniform as possible in the imaging region. The uniform sensitivity leads to better conditioned sensitivity matrix, because the ratio between the maximum and minimum matrix elements will be smaller, which leads to smaller ratio between the maximum and minimum matrix eigenvalues (called condition number). The smaller condition number of the sensitivity matrix leads to better convergence of the inverse problem solution by iterative methods (e.g., Gauss-Newton method).

Additional goal here is to compare the two shielding constructions: a) Fig 1a - with grounded conducting strips between the electrodes; b) Fig. 1b - with grounded conducting radial bars between the electrodes.

3. FORMULATION OF THE OPTIMIZATION PROBLEM

The optimization of an ECT sensor can be formulated as a general constrained optimization problem:

Minimize

(1) $S_{diff} = (S_{\max} - S_{\min}) / S_{aver}$, for all pixels where S is positive,

where $\mathbf{x} = \{ g_a, s_a, d_{ins}, \varepsilon_{r\_ins}, , d_{pipe}, \varepsilon_{r\_pipe} \}^t$ is the vector of design variables:

g_a - gap/(electrode division) ratio; s_a - shield/gap ratio, d_{ins} - insulation layer thickness; ε_{r_ins} - insulation layer relative permittivity; d_{pipe} - pipe wall thickness; ε_{r_pipe} - pipe wall relative permittivity.

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Subject to the constraints (can be selected regarding to the ECT measurement system abilities):

(2) $C_{\min} > 0.01 pF$; $C_{\max} < 1 pF$;

The sensitivity in every pixel of the sensitivity map for the pair *i-j*, is computed using the formula:

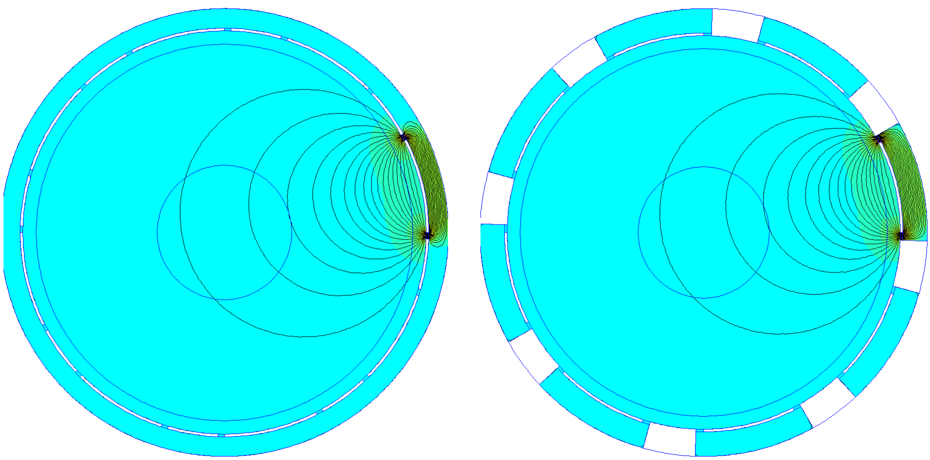
$$S_{ij} = -\int_{\Omega} \mathbf{E}_i \cdot \mathbf{E}_j d\Omega , \tag{3}$$

where $\mathbf{E}_i$ is the electric field inside the sensor when the electrode *'i'* is excited as a source electrode, $\mathbf{E}_j$ is the electric field when electrode *'j'* is excited as a source electrode. The electric field intensities in every pixel of the image are found by using FEM. The excitation of every single electrode in turn is 1V. The set of sensitivities for an electrode pair is known as the sensitivity map of that pair.

4. IMPLEMENTATION USING FEMM AND MATLAB

For this optimization the distribution of the electric field has been found by the finite element method and the software package FEMM [5]. The electric field intensities have been computed in the centers of the square cells of rectangular grid of 100 by 100 divisions, covering the imaging area inside the pipe. Then using Eq. 3, the sensitivity matrix has been computed. The normalized difference between its maximum and minimum positive elements has been computed as an objective function. In order to be used by the optimization program, the FEMM must be controlled by a parameterized script, which creates new sensor geometry for every new set of input parameters. This script is programmed in the Lua-language [5], and is called by the fitness and constraint functions of the genetic algorithm program [4].

The meshes created by FEMM vary between 7000 and 10000 elements, and the time for a single evaluation (consisting of 8 FEM analyses with different electrode excited) is about 1s on a PC with Intel Core 2 Duo T6500 2.1 GHz CPU with 3 GB RAM. Special measures have been taken to avoid calling FEMM for same set of parameters, which diminishes the



a) b)

Fig. 2. Equipotential lines for the case when the first electrode is excited:
a) strip shields, b) bar shields

objective function evaluations. The whole optimization process takes 2-2.5 hours computing time. The constrained optimization has been performed using the genetic algorithm from Matlab Global Optimization Toolbox [4] (with population of 10 members and 10 generations).

5. RESULTS

The optimum results for the sensor sizes and permittivity values due to its sensitivity distribution, obtained for the first ECT sensor case (strip shields between the electrodes) are shown in Table 1. The optimum results for the second case are shown in Table 2.

Table 1. Parameters values and goal function value S_{diff} for initial and optimum variants, strip shields. Computation time – 2h 01s

Variant	g_a	s_a	d_{ins}	ε_{r_ins}	d_{pipe}	ε_{r_pipe}	S_{diff}
Initial	0.01	1	14 mm	2	3 mm	3	43.2
Optimal	0.083	3.8	7.3 mm	1.48	4.98 mm	1.037	4.668

Table 2. Parameters values and goal function value S_{diff} for initial and optimum variants, bar shields. Computation time – 2h 20s

Variant	g_a	s_a	d_{ins}	ε_{r_ins}	d_{pipe}	ε_{r_pipe}	S_{diff}
Initial	0.01	1	14 mm	2	3 mm	3	43.13
Optimal	0.099	3.04	9.36 mm	1.33	4.99 mm	1.26	4.7

It can be seen that the uniformity of the sensitivity maps is improved considerably – the objective function - the variance of the sensitivity, is diminished approximately 8 times, compared with the initial variant. The initial variant is taken as the typical in the practice design with very small air gap between electrodes (1/100 of the electrode division), usually done to use the surface of the cylinder as much as possible for electrodes, thus increasing the capacitances. However, this design leads to high concentration of the field intensities near the excited electrodes and high sensitivity in these regions, which in turn destroy the uniformity of the sensitivity distribution. The role of the optimization is evident – the algorithm increases the sizes of the air gaps to reduce the electric intensity values near the electrodes and to improve the sensitivity uniformity in whole sensor imaging area.

It is seen from Tables 1 and 2, that in respect to the uniform sensitivity the two designs are nearly the same - the objective function is 4.668 in the first case and and 4.7 in the second case, with slightly different parameters, at which this minimum is obtained. The first case, however, is better for the practical constructions because the strip shields can be easily created on printed-circuit folio. The shielding bars in the second case are more difficult to be fabricated and mounted.

Table 3. Comparison of the mutual capacitances for the two shielding cases

Capacitance, pF	C_{1-2}	C_{1-3}	C_{1-4}	C_{1-5}	C_{1-6}	C_{1-7}	C_{1-8}
Strip shields	2.0449	0.06636	0.03603	0.03031	0.03603	0.06636	2.0452
Bar shields	1.3823	0.06636	0.03603	0.03031	0.03603	0.06636	1.3822
Difference %	32.4	0.00039	0.0009	0.00079	0.00006	0.00033	32.4

The same similarity can be seen from the Table 3, where the mutual capacitances for both shielding cases are shown. The only difference is in the capacitances between the adjacent electrodes – it is 32.4%, and is probably caused by the different distribution of the field between the adjacent electrode – in the case of the bar shields, the field is better screened and does not enter the region behind the neighboring electrode. For all other capacitances the differences are negligible and comparable with the discretization errors.

6. CONCLUSIONS

The paper shows an optimization by Genetic Algorithm applied to obtain optimum sizes of an 8-electrode ECT sensor with maximum uniformity of the sensitivity maps. The results show the effectiveness of this approach. It could be used also for optimization of 3D multilayer ECT sensors and authors plan to do this in the near future. The computation time of one field calculation in 3D is considerably higher and does not allow using a genetic algorithm alone in the optimization. In this case, a combination of Response Surface Methodology (RSM) and GA can be applied, performing the optimization over approximating polynomial models. Parallel computations of the objective function can be used also, if multicore CPUs (6-8 cores) are used for the optimization. This could diminish substantially the optimization time, as the GA belongs to the class of the *embarrassingly parallel problems* – the evaluations of the fitness functions of the members of one generation are independent one from another and can be done in parallel without interaction and communication between them.

Another conclusion is, that the strip shields and the bar shields between the electrodes have nearly the same effect on the capacitances and the sensitivity distribution in the imaging region. In the next development the optimized sensors will be used to solve the inverse problem and to evaluate the probable improvement in the obtained reconstruction images.

7. REFERENCES

[1] **Alme K.**, S. Mylvaganam, Electrical capacitance tomography - sensor models, design, simulations, and experimental verification. IEEE Sensors Journal, Vol. 6, No. 5, October 2006, 1256-1266.

[2] **Marashdeh Q.**, L. Fan, B. Du, and W. Warsito. Electrical Capacitance Tomography - A Perspective. Ind. Eng. Chem. Res. 2008, 47, pp. 3708-3719.

[3] **Yang W.Q.**, Design of electrical capacitance tomography sensors, Meas. Sci. Technol. 21 (2010) 042001 (13pp);

[4] **Matlab R2008a,** Genetic Algorithm and Direct Search Toolbox.

[5] **Meeker D.C.**, (2010), Finite Element Method Magnetics, Version 4.2, available at: http://femm.foster-miller.net (last update 2 Nov 2009).

[6] **Olmos A.M.,** J. Alberdi Primicia and J. L. Fernandez Marron, Influence of Shielding Arrangement on ECT Sensors, Sensors 2006, 6, pp. 1118-1127.

[7] **Olmos A.M.**, J. Alberdi Primicia and J.L. Fernandez Marron, Simulation design of electrical capacitance tomography sensors, IET Sci. Meas. Technol., 2007, 1, (4), pp. 216–223.

OPTYMALIZACJA CZUJNIKA ECT Z WYKORZYSTANIEM ALGORYTMÓW GENETYCZNYCH

Streszczenie

Niniejszy artykuł prezentuje proces optymalizacji 8-elektrodowego sensora elektrycznej tomografii pojemnościowej o przekroju walcowym wyposażonego w dwa rodzaje systemów wewnętrznego ekranowania. Celem tej optymalizacji jest uzyskanie jednorodnego rozkładu map czułości sensora przy zachowaniu wartości pojemności wzajemnych powyżej ustalonego poziomu. Na potrzeby prezentowanego procesu optymalizacji zastosowano Algorytmy Genetyczne. Wynikiem przeprowadzonych badań są wyznaczone podstawowe optymalne parametry geometryczne struktura czujnika pojemnościowego pod kątem jednorodnego rozkładu czułości.

Politechnika Łódzka
Katedra Informatyki Stosowanej