Modelling complex electromagnetic sources for microwave imaging systems with wave field synthesis technique

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Presented is a methodology for the synthesis of complex electromagnetic sources based on the wave field synthesis. In particular, the wavefront of a propagating electromagnetic wave, generated by a suitable antenna, is synthesised using a set of point sources with specific amplitudes and phases, calculated with a suitable optimisation algorithm. This approach permits a reduction of the descriptive parameters of the scenario under consideration, a strong reduction of the computational resources and consequently a reduction of computational time necessary to simulate the scenario under investigation. The obtained results have been assessed considering experimental measurements, in particular an ultra-wideband antenna of a real microwave imaging system for breast cancer detection, has been considered. The agreement between numerical and experimental data is quite good.

Introduction: In the last decade the use of microwave imaging techniques for biomedical applications has become a promising technique for early breast cancer diagnosis. Microwave imaging could be a valid supplement or alternative to X-ray mammography due to the non-ionising nature of microwave radiation and the superior electrical contrast at microwave frequencies. In such a framework an efficient modelling of the electromagnetic source is desirable for the application of microwave imaging techniques in real enviroments [1]. A microwave imaging system is usually based on the solution of an inverse problem, whose accuracy strongly depends on the correct modellisation of the field source. Towards this end, an accurate but simple model (i.e. requiring reasonable computational resources) of the field source should be developed. Numerical methods permit accurately reproducing real data but they are quite complicated to implement [2], especially if the number of electromagnetic field samples collected in a portion of the so-called observation domain is limited; moreover, these techniques require high computational resources. On the other hand, a coarse model could introduce erroneous constraints in the reconstruction process. In this reported work, the wave field synthesis (WFS), a technique originally developed to generate sound fields by arrays of loudspeakers, has been used to synthesise a current distribution that produces the same radiated field of a wide-slot antenna with an array of source points. In this way a simplified and accurate antenna model, useful to model a realistic microwave imaging scenario for breast cancer detection, has been obtained. The obtained model needs limited computational resources and it has been assessed with experimental measurement.

Synthesis of wide-slot antenna with WFS: Wave field synthesis is a spatial sound field reproduction technique that uses a high number of loudspeakers to create a virtual auditory scene over a large listening area. The WFS was formulated by Berkhout almost twenty years ago [3, 4]. In recent years there has been a growing interest in this technique since it can be extended from the synthesis of acoustic fields to the synthesis of complex electromagnetic sources. In particular, in this Letter the WFS is used to model a complex wide-slot antenna with a set of point sources with the goal of obtaining a simplified model of the electromagnetic source that requires a limited amount of computational resources. Let us consider the problem of synthesising a current distribution that produces a target electromagnetic field $\underline{E}_a(\underline{r}_m, \omega)$ in a given spatial area $\Sigma \in \Re^3$ by M distributed point sources placed at fixed locations $\underline{r}_m$, $m = 1, \ldots, M$. The point sources belong to a given media characterised by an electric permittivity ε_r, an electric conductibility σ_t, and they present a spectra $\tilde{S}_m$, $m = 1, \ldots, M$, $h = 1, \ldots, H$, which is the same spectra of the target field $\underline{E}_a(\underline{r}_m, \omega_h)$, $h = 1, \ldots, H$, H being the considered frequency time steps. If monopoles are considered as point sources they will synthesise an electromagnetic field (called trial field) given by the following:

$$\underline{E}(\underline{r}, \omega) = \sum_{m=1}^{M} \sum_{h=1}^{H} \tilde{S}_m(\omega_h) \frac{e^{\frac{j\omega_h}{V}|\underline{r} - \underline{r}_m|}}{4\pi|\underline{r} - \underline{r}_m|} \qquad (1)$$

At this point the synthesis problem can be recast into an optimisation problem by defining a suitable cost function that defines the error between the target field and the trial field as follows:

$$\Phi(\Delta = \{\tilde{S}_m(\omega_h); m = 1, \ldots, M \; h = 1, \ldots, H\}) = \int_{\Gamma} \sum_{h=1}^{H} |\underline{E}_a(\underline{r}, \omega_r) - \underline{E}_t(\underline{r}, \omega_h)| ds \qquad (2)$$

where $\Delta = \{\tilde{S}_m(\omega_h); m = 1, \ldots, M \; h = 1, \ldots, H\}$ is the spectra generated by the M sources, $\underline{E}_a(\underline{r}, \omega_h)$ and $\underline{E}_t(\underline{r}, \omega_h)$ are the target field and the trial synthesised field, respectively, and V is the propagation velocity of the electromagnetic wave in the coupling medium ($\varepsilon_r = 9$, $\sigma = 0.2[S/m]$). The minimisation of (2) is obtained by constructing a sequence of trial solutions Δ_s^k (s being the trial solution index, and k the iteration index $k = 1, \ldots, K_{\max}$) following the strategy of a suitable optimisation algorithm, namely the bee algorithm. The bee algorithm is an algorithm inspired by the natural behaviour of the honey bee. The population of bees is divided into employer and onlooker bees. The onlooker bees move randomly from a path to another in the solution space to try to find the best solution. They change their direction after a fixed number of steps $L_{\max}$. Then they come back to the nest and share the information with the other bees of the swarm [5]. The iterative optimisation algorithm continues until the stopping criteria are reached. In particular, when $k = K_{\max}$ or $\Phi(\Delta_s^k) < \beta$, where $K_{\max}$ and β are the maximum number of iterations and a convergence threshold, respectively. At the end of the iterative procedure the optimal solution defined as $\Delta^{opt} = arg\{min[\Phi(\Delta_k)]\}$ is stored, and the obtained weight used for the simplified numerical model devoted to the simulation of the electromagnetic source.

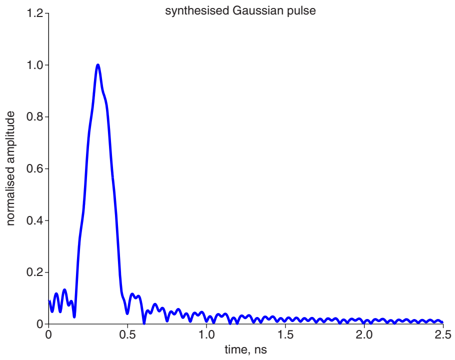

Fig. 1 *Synthesised Gaussian pulse, used to feed antenna, obtained with measured complex weights*

Numerical assessment: To assess the capabilities of the proposed synthesis method the experimental microwave imaging system, described in [6], has been considered. The system consists of $p = 31$ wide-slot antennas [7], disposed along a hemisphere. The antennas can act as transmitters or as receivers. For this preliminary experiment the wide-slot antenna positioned at ($x = -50.7$ mm, $y = -51.9$ mm, $z = -46.4$ mm), will be synthesised. The electromagnetic field data required by the wave field synthesiser are collected with 30 probes and considering an uniform coupling medium (fat). A Gaussian pulse synthesised with 100 sinusoidal tones ranging from 3 GHz up to 10 GHz with frequency steps of 70 MHz has been considered as the excitation signal. The synthesised pulse is reported in Fig. 1. The field measured at the 30 probes is used as input data for the WFS methodology. In particular, to synthesise the slot aperture antenna described in [7] and reported in Fig. 2, $M = 16$ source points equally distributed along the antenna aperture have been considered. The total number of complex weights necessary to synthesise the same electromagnetic field produced by the slot antenna are $S = 2 \times M \times H = 1600$. The ABC parameters have been chosen after a preliminary calibration procedure. In particular, a random initial population of $C = 200$ individuals (100 onlookers and 100 employers) and $L_{\max} = 5$ has been considered. The computational time required to perform the synthesis on a personal computer equipped with an AMD Athlon (TM) 600+ quad-core processor with 4 GB RAM is about 55 minutes. The synthesis method previously described has been applied to model the wide-slot antenna reported in [7]. In particular, the algorithm operates for each of the 100 considered frequency tones. The iterative procedure reaches a stationary condition after about 500 iterations. The synthesised field has been obtained starting from the weight obtained with the iterative synthesis methodology, and considering an FDTD electromagnetic engine. The difference between the measured and synthesised field is less than one per cent, for all the considered measurement points. For the sake of comparison, Fig. 3 shows the comparison between the measured and synthesised electric field at one probe. In particular, Fig. 3 reports the modulus of the electric field along the z-axis; as can be noticed, the synthesised field is in good agreement with the measured field. With the proposed model based on $M = 16$ points source it is possible to reach a computational saving of about 65%.

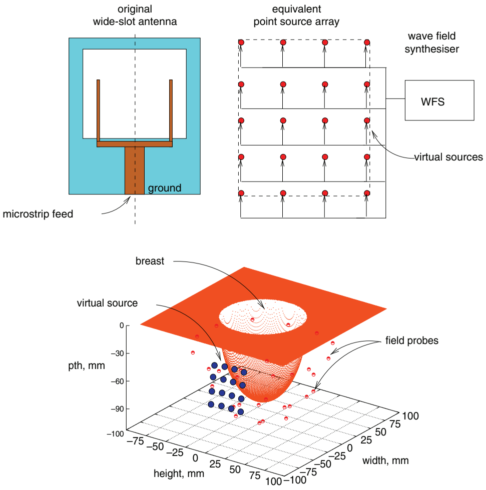

Fig. 2 *Geometry of wide-slot antenna; corresponding wave field synthesiser; considered experimental setup*

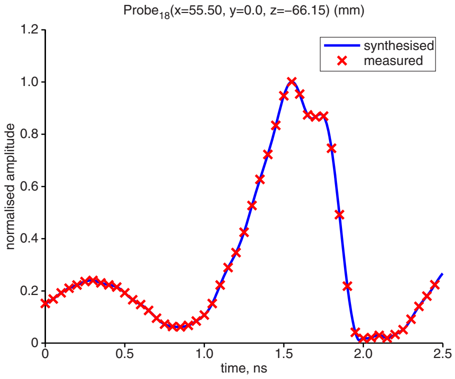

Fig. 3 *Comparison between measured and synthesised field obtained with synthesised complex weights at probe 18*

Conclusion: In this reported work the wave field synthesis has been successfully used to model complex electromagnetic sources, namely a broadband antenna for a microwave imaging systems. This task has been accomplished by applying the WFS and an optimisation algorithm, namely the bee algorithm. The obtained results, that consider experimental data, demonstrate the potentialities of the proposed method to model realistic microwave imaging scenarios.

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One or more of the Figures in this Letter are available in colour online.

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References

1 Franceschini, D., Donelli, M., and Massa, A.: 'On the effects of the electromagnetic source modeling in the iterative multiscaling method', *Radio Sci.*, 2007, **42**, pp. 1–17

2 Hill, D.A.: 'A numerical method for near-field array synthesis', *IEEE Trans. Electromagn. Compat.*, 1985, **5**, pp. 201–211

3 Berkhout, A.J.: 'A holographic approach to acoustic control', *J. Audio Eng. Soc.*, 1988, pp. 977–995

4 Boone, M.M., Verhejen, E.N.G., and Tol, P.F.: 'Spatial sound field reproduction by wave field synthesis', *J. Audio Eng. Soc.*, 1955, pp. 1003–1012

5 Karaboga, E., and Akay, B.: 'A comparative study of artificial bee colony algorithm', *J. Appl. Math. Comput.*, 2009, pp. 108–132

6 Donelli, M., Craddock, I., Gibbins, D., and Sarafianou, M.: 'A three-dimensional time domain microwave imaging method for breast cancer detection based on an evolutionary algorithm', *Prog. Electromagn. Res. M*, 2011, **18**, pp. 179–195

7 Gibbins, D., Klemm, M., Craddock, I., Leendertz, A., Preece, A., and Benjamin, R.: 'A comparison of a wide-slot and a stacked patch antenna for the purpose of breast cancer detection', *IEEE Trans. Antennas Propag.*, 2010, **5**, pp. 20–23