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Some Improvements to Field Intensity Shaping for Biomedical Applications: Preliminary results

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Abstract

In this contribution some recent advances in field intensity shaping paradigm are introduced and discussed, with particular emphasis on biomedical applications. Attention is focused on the design of the complex excitations feeding a biomedical array applicator such to ensure uniform and maximum field intensity distribution inside a given region of interest, while keeping it under control in some other regions. In particular, a smart procedure for the selection of the optimal phase shifts underlying *multi control points*-based approaches is introduced. Note that this procedure also plays a key role in other relevant non biomedical applications, including satellite and radio communications, as well as in antenna array synthesis theory.

1. Introduction

The shaping of field intensity is relevant in many biomedical applications. First of all, the need of focusing the field intensity in tumoral cells to increase their temperature, while avoiding the heating of the surrounding health tissues, plays a key role in microwave hyperthermia treatment (MHT) [1],[2]. Indeed, if cells are heated beyond their normal temperature, they become sensitized to therapeutic agents such as radiation and chemotherapy. Moreover, in magnetic resonance imaging (MRI), there is the requirement to ensure the homogeneity of the amplitude of the radiofrequency field, in order to obtain high-quality and high-resolution images [3],[4]. However, the issue of leveling or shimming the radiofrequency field must be addressed by also limiting the specific absorption rate (SAR).

The above applications involve the capability and the ability to enforce a given behavior to the electromagnetic field distribution. In particular, the following issues are usually addressed: a) maximum and uniform field intensity distribution in a given target area, that is the tumor in MHT or the anatomical region to be imaged with MRI; b) keeping under control the field amplitude in some other areas, that are surrounding health tissues in MHT or the whole patient body in MRI.

In order to address the above requirements, we exploit the recent shaping techniques based on the use of *multi control points* set in the given target area [5],[6]. These techniques rely on many patterns focused on the considered control points and combine them by considering different phase shifts, representing the phase difference between the fields in the control points and in the reference point. By exploring all the possible phase shifts, one can select the optimal solution for the application at hand. However, the exploration of all the possible phase shifts implies a high computational burden, especially in case of extended target region, and this may prevent the use of *multi control points*-based approaches in real world applications.

In this contribution, a smart procedure for the selection of the optimal phase shifts based on the concept of destructive and constructive interferences is proposed. This procedure is able to limit the set of convenient phase shifts to be explored to find the optimal solution and then allow to drastically reduce the computational burden related to *multi control points*-based techniques, as briefly explained in the following.

2. Statement of the problem

Let us consider N elementary monochromatic electric sources surrounded the bidimensional region of interest Π, with known electrical properties, i.e. relative permittivity $\epsilon_x(\underline{r})$ and electric conductivity $\sigma_x(\underline{r})$. The region Π is embedded in a homogeneous domain Ω, with known electrical properties (ϵ_b, σ_b).

The aim of the problem is to determine the optimal set of complex excitation coefficients I_n feeding the array applicator such to produce the desired behavior of the electromagnetic (magnetic or electric field) amplitude in Π, while enforcing some constraints in Ω. In both MHT and MRI shimming, one needs to ensure a uniform and sufficiently intense field amplitude in Π, while limiting the SAR in $\Omega\backslash\Pi$ as far as MHT, and in Ω as far as MRI shimming.

According to *multi control points*-based techniques, the relevant shaping problem can be addressed as follows [5],[6]:

$$I_n = arg\ max\ \mathcal{R}e\left\{\psi\left(\underline{r}_{t_0}, I_n\right)\right\} \tag{1.a}$$

subject to:

$$\Im m\{\psi(\underline{r}_{t_0}, I_n)\} = 0 \quad (1.b)$$

$$\mathcal{R}e\{\psi(\underline{r}_{t_i}, I_n)\} = \mathcal{R}e\{\psi(\underline{r}_{t_0}, I_n)\}cos\phi_i \quad (1.c)$$

$$\Im m\{\psi(\underline{r}_{t_i}, I_n)\} = \mathcal{R}e\{\psi(\underline{r}_{t_0}, I_n)\}\sin\phi_i \quad (1.d)$$

$$SAR(\underline{r}, I_n) \leq UB(\underline{r}) \quad (1.e)$$

wherein $\underline{r} \in \Omega$ in MRI and $\underline{r} \in \Omega\backslash\Pi$ in MHT; $\underline{r}_{t_0}$ is a given point in Π which is assumed as reference point; r_{t_i} (i $= 1, \ldots, L$) are L controls points belonging to Π. ψ is the total electric or magnetic field (depending on the application at hand) due to the N elementary sources; $\phi_i \in [0,2\pi[$ are the auxiliary variables indicating the phase shifts between the fields in $\underline{r}_{t_0}$ and $\underline{r}_{t_i}$. $\mathcal{R}\{\cdot\}$ and $\Im\{\cdot\}$ are the real and the imaginary parts, respectively.
Note that other additional constraints can be eventually added to problem (1). For instance, in MRI shimming, once can also enforce polarization purity [7].

For any fixed combination for ϕ_i, problem (1) recasts the shaping problem as the maximization of a linear function in a convex set, which corresponds to a convex programming (CP) problem. Then, the globally optimal solution of overall optimization problem can be a posteriori determined by looking into the values of the cost function or some performance indicators achieved in the different CP problems.

3. Rationale of the proposed method

M*ulti control points*-based techniques have already shown satisfactory performance both in telecommunication and MHT applications. However, when just a few control points are of interest, one can explore the different possible combinations for ϕ_i by enumerative optimization [5],[6] or alternatively by global optimizations [8]. However, such approaches become less effective as the number of control points grows. This circumstance may significantly prevent the use of *multi control points*-based techniques.

Then, the aim of this contributions it to introduce a smart procedure to a priori (that is before the optimization of problem (1) at hand) select the optimal phase shift or the optimal set of phase shifts for a given configuration of control points. The proposed procedure exploits the physic underlying destructive and constructive interferences of waves.

In order to show and better understand the rationale of the proposed strategy, let us consider the shaping problem (1) in case of free space and three control points. Under the above, the constraints (1.c) and (1.d) ensuring uniformity are given by:

$$\mathcal{R}e\{\psi(\underline{r}_{t_1}, I_n)\} = \mathcal{R}e\{\psi(\underline{r}_{t_0}, I_n)\}cos\phi_1 \quad (2.a)$$

$$\Im m\{\psi(\underline{r}_{t_1}, I_n)\} = \mathcal{R}e\{\psi(\underline{r}_{t_0}, I_n)\}\sin\phi_1 \quad (2.b)$$

$$\mathcal{R}e\{\psi(\underline{r}_{t_2}, I_n)\} = \mathcal{R}e\{\psi(\underline{r}_{t_0}, I_n)\}cos\phi_2 \quad (2.c)$$

$$\Im m\{\psi(\underline{r}_{t_2}, I_n)\} = \mathcal{R}e\{\psi(\underline{r}_{t_0}, I_n)\}\sin\phi_2 \quad (2.d)$$

wherein $\phi_1, \phi_2 \in [0,2\pi[$. In order to select the optimal pair (ϕ_1, ϕ_2), one can sample the set $[0,2\pi[\times[0,2\pi[$ in a certain number of pairs and solve a CP problem for each one. Then, the optimal pair (ϕ_1, ϕ_2) , that is the combination of phase shifts giving the optimal field intensity distribution, is a posteriori evaluated by means of some performance indicators (for instance, the standard deviation of the field amplitude in Π or the average amplitude of the field in the Π) [5],[6].

On the other hand, we know that the *multi control points*-based techniques rely on the combination of different field patterns focused on $\underline{r}_{t_i}$ by means of a proper phase shift. As the field patterns are focused on the control points, they can be approximated by means of L zero order Bessel functions J_0, each centered in $\underline{r}_{t_i}$. As a consequence, in case of three control points, in order to off-line select the optimal phase shift or the optimal set of phase shifts, the total field induced in the region of interest Ω can be approximated and then analyzed by considering the simple superposition of three Bessel functions, i.e.:

$$\psi(\underline{r}) \approx J_0(k_m|\underline{r} - \underline{r}_{t_0}|) + J_0(k_m|\underline{r} - \underline{r}_{t_1}|)e^{j\phi_1} + J_0(k_m|\underline{r} - \underline{r}_{t_2}|)e^{j\phi_2} \quad (3)$$

wherein k_m is the average wave number evaluated within Π. Once $\underline{r}_{t_0}$,$\underline{r}_{t_1}$ and $\underline{r}_{t_2}$ are located in Π, by exploiting eq. (3), one can a priori (off-line, that is independently from the specific situation at hand and before the final optimization of problem (1)) select the optimal pair or the set of optimal pairs (ϕ_1, ϕ_2), without the need of explore all the possible values in $[0,2\pi[\times[0,2\pi[$ and thus reducing the computational burden related to *multi control points* -based techniques.

4. A preliminary numerical example

The domain Ω under test is depicted in Figures 1(a). A square domain of side $L = \lambda_b$ discretized into 60×60 cells is considered, being λ_b the wavelength in free space. The control points are located at a distance of $0.3\,\lambda_b$, while the region of interest Π is represented by the yellow triangle in Figure 1(a).

The spatial distributions of the field intensity obtained by considering some phase shift pairs are reported in Figure 1(b)-(e). As can be seen, in some cases, a disruptive interference arises between the two Bessel functions. Instead, for other phase shift values close to 0 a satisfactory tradeoff between amplitude and uniformity is obtained. Then, according to the proposed off-line procedure, the pairs $(\phi_1, \phi_2) = (0,0)$ and $(0.314, 0.924)$ are optimal phase shifts to be considered in the final optimization of problem

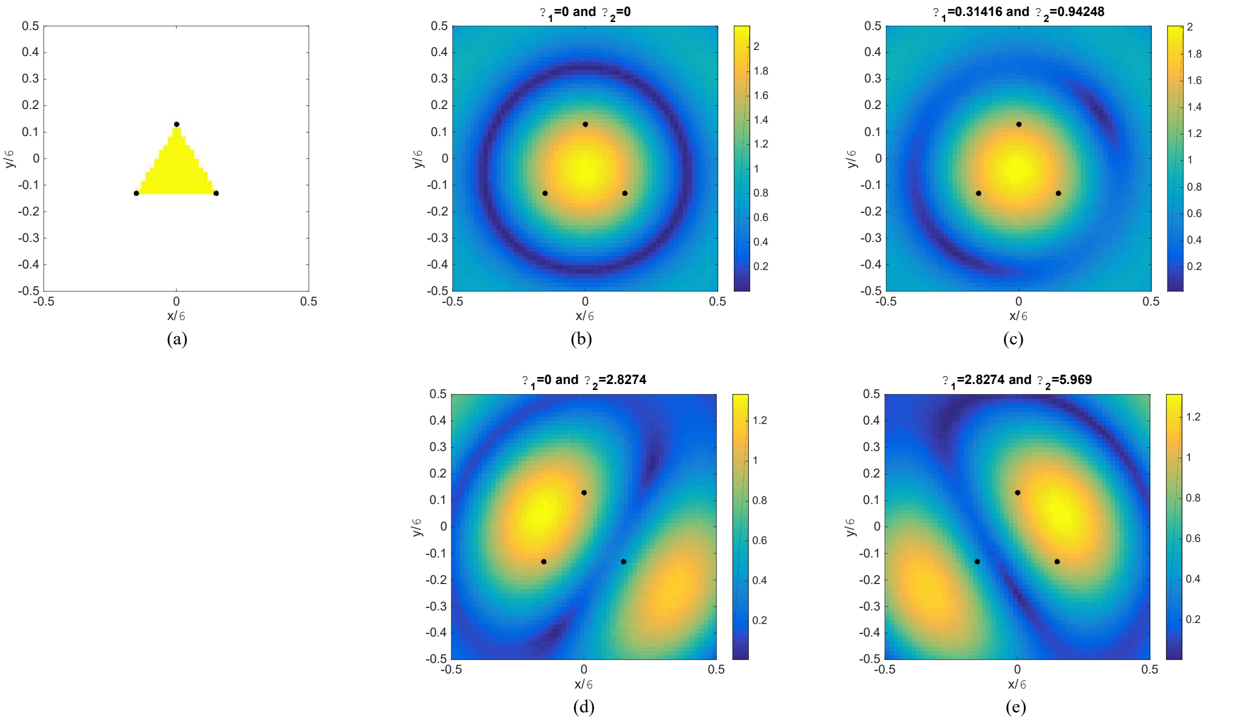

Figure 1. Assessment of the proposed off-line selection procedure of the optimal phase shifts in case of three control points. (a) Scenario under test in free space: $d_{01} = 0.3\lambda_b$, $d_{02} = 0.3\lambda_b$ and $d_{12} = 0.3\lambda_b$. Π is the yellow area, while the control points are superimposed as black points. (b)-(e) Spatial distributions of the field intensity corresponding to some phase shift pairs.

(1), in case of three control points with distances $0.3\lambda_b$, whatever the applications at hand. In case of MRI shimming, the shaping results have been compared with the enumerative approach in [5],[6], and same performance have been obtained. However, the number of CP problems solved is drastically reduced with respect to M^2, being M=20 the number of samples in $[0,2\pi[$.

More details about the proposed approach, as well as numerical examples against MHT and MRI shimming showing the good performance of the above selected optimal phase shifts, will be given at the conference.

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