Numerical Methods in Bioelectromagnetics Analysis

Metody numeryczne w analizach bioelektromagnetycznych

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Abstract — The paper is devoted to short characteristic of numerical methods using in electromagnetics investigations. Three main methods were presented: Method of Moments, Finite Element Method and Finite Difference Time Domain method. FEM and FDTD were used in computer simulations to show the interaction between the exposure system and tested object.

Index Terms — : electromagnetic fields, bioelectromagnetics, numerical methods, exposure system, TEM cell, accuracy of biomedical studies

Streszczenie - artykuł poświęcony jest krótkiej charakterystyce metod numerycznych wykorzystywanych w badaniach bioelektromagnetycznych. Omówiono trzy podstawowe metody: metodę momentów, metodę elementów skończonych i metoda różnic skończonych w dziedzinie czasu. Metody elementów skończonych i różnic skończonych zostały wykorzystane w symulacjach komputerowych na potrzeby wyznaczenia wzajemnego oddziaływania między układem ekspozycyjnym, a badanym obiektem.

Słowa kluczowe - pole elektromagnetyczne, bioelektromagnetyzm, metody numeryczne, układy ekspozycyjne, komora TEM, dokładność badań biomedycznych.

INTRODUCTION

It is well known that the primary tool for quantitative research is hands-on experimentation and measurements. Unfortunately, the tests are not always possible due to high complexity of the studied objects, lack of appropriate sensors or their inaccuracy. This is especially important in the measurement of electromagnetic field (EMF). It is worth mentioning that any physical quantity measured (i.e.: frequency) are performed with $10^{-10\%}$ accuracy, whereas the error in creating a standard EMF equals 5% ÷ 10%. That influences the test tools' accuracy whose error can't exceed the one of creating EMF. Further appears the question of ethics of such tests. Experiments examining EMF's influence on human body are acceptable with person's consent, but still controversial. The same applies to the use of animals for this type of research. Above arguments show that bioelectromagnetic testing is a challenge, and is often impossible to perform. This is where use of mathematical models and computer programs based on numeric methods comes in handy. These tools give us some insight on the expected results. Similar results from different numerical methods can be considered as exemplary and reliable.

Thermal And Non-Thermal Effects Of EMF

The first effects of the EMF on the human body has been identified in the nineteenth century by Jacques Arsene d'Arsonval, who was engaged in, among others, study of electrical phenomena occurring in the muscles. It was him, who introduced the current diathermic treatment. He was a pioneer in electrotherapy. He observed both, thermal and non-thermal effects of EMF [1][2].

The result of thermal impact on the body is the temperature rise of tissues and body fluids causing pathological changes and physiological responses caused by the tissues increased temperature. The increase in frequency causes an increase in the threshold current density. It also raises the intensity of energy absorption and causes thermal effects, which dominate at frequencies above 10 MHz. The temperature raise depends on many factors, such as: field strength, frequency, and individual characteristics of the person undergoing the exposure.

When it comes to non-thermal effects, the changes in the

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body are caused without raising the temperature of the tissues. These effects occur at low field intensities and at different levels of biological organization. They dominate at low frequencies (up to 100 kHz), where the absorption of electromagnetic energy by the body is weak. The most important non-thermal effects included are [3]-[8]:

- membrane stimulation of excitable tissues, due to the presence of induced,
- transport abnormalities of ions of calcium, potassium and sodium,
- memory disturbances,
- changes in blood smears and EEG records,
- sleepiness,
- fatigue,
- functional disorders of the nervous system.

The question of existence of non-thermal effects is still a subject of dispute among scientists and has so far not been clearly resolved. This leads to increased research in this area, which is shown in numerous publications. In addition, we observe the non-specific effects. They are linked to the fact that some people associate their health problems with increased sensitivity to EMF [9]. Some of the non-specific effects may include:

- headache,
- dizziness,
- sleep disturbances,
- sensation of heat,
- abnormal heart rate,
- shortness of breath.

The non-specific symptoms are reported, but they cannot be confirmed experimentally. According to the Scientific Committee on Toxicity, Ecotoxicity and the Environment, there is the possibility of a hypersensitivity to EMF in a small group of people. It is necessary to confirm this fact, though the report of this type of research cannot be relied on in conducting the limits of EMF exposure in the regulatory laws [5].

Besides the negative effects, electromagnetic field can also have a positive impact on living organisms. Those effects are used for diagnostic purposes and have various applications in medicine. Some of them are [10]-[12]:

- breast cancer detection,
- skin cancer treatment,
- treatment of depression,
- analgesia,
- orthopedics,
- degenerative and rheumatic diseases,
- inflammation of the joints and muscles.

As it can be seen from the above examples, the omnipresence of EMF is not indifferent to living matter, and under certain conditions can cause various biological and health effects [13].

It all points to the necessity of studying subjects related to the EMF's effect on living organisms and defining measures of these effects, as well as field measurements and their accuracy and exposure systems used during the production of the EMF. The best, fast and safe methods for thouse analysis are numerical methods.

MATERIALS AND METHOD

Computational methods for electromagnetism are dated back to the sixties of the twentieth century. Today's software is based on electromagnetic field theory, and takes into account both physical phenomena, and numerical methods. Some of the most important ones are: Moment Method (MoM), Finite Element Method (FEM) and Finite Difference Time Domain method (FDTD).

A. Moment Method

Moment method was created by Harrington in 1968 [14]. It is mainly used for solving operator-based equations like [15][16]:

$$Lf = g \tag{1}$$

where:
L – linear operator,
g – known excitation function ($g = g(X)$),
f – sought function, $f = f(Y)$,
X, Y- coordinates in a multidimensional space,

Sought approximate solution is presented in a form of a sum:

$$f(Y)=\sum_{i=1}^{n} a_i f_i(Y) \tag{2}$$

where:
$f_i(Y)$ – known set of linearly independent functions, which in the case of n → ∞ must provide an exact solution [17],
a_i – unknown coefficients.

Substituting equation (2) into (1) we get:

$$\sum_{i=1}^{n} a_i\, Lf_i = g \tag{3}$$

In order to determine the coefficients a_i, one should choose a set of stable, weighted functions $w_j(X)$, $j = 1,\ldots,n$ and multiply equation (3) by a weighted scalar. This will result in a set of linear equations in the following form:

$$\sum_{i=1}^{n} a_i \langle w_j, Lf_i \rangle = \langle w_j, g \rangle \quad , j = 1,\ldots,n \tag{4}$$

Obtained solution (4) may be exact or approximate, and the accuracy depends on the choice of functions f_i and w_j [14].

B. Finite Element Method

The history of FEM dates back to the fifties of the twentieth century where it was used for calculations in structural mechanics [18]. It was not until thirty years later that the method was applied to the EMF's boundary value problems [19].

The basis of the FEM method is to divide the examined area into the elements, depending on the type of the problem [20]:

- one-dimensional - sections,
- two-dimensional - triangles or quadrangles,
- three-dimensional - tetrahedral.

Each element has its nodes which are linked to sought field sizes. In order to share nodes (and their field sizes) between neighboring elements, nodes are usually located on the element's sides or corners. Some types of elements have interpolated nodes located in the middle of the element.

Inhomogeneous Helmholtz equation (5) is a typical wave equation commonly seen in electromagnetism:

$$\nabla^2\phi + k^2\phi = g \tag{5}$$

where:

ϕ – sought field size,

g – source function,

k – propagation constant ($k = \omega\sqrt{\varepsilon\mu}$).

The above equation is found in three different cases:

- $k = g = 0$ – Laplace equation,
- k = 0 – Poisson equation,
- g = 0 – Helmholtz homogeneous scalar equation.

Minimizing the functional is necessary in order to find a solution to the nonhomogeneous wave equation [19][20]

$$F(\phi) = \frac{1}{2}\iint_{\Omega}\left[\left|\nabla\phi\right|^2 - k^2\phi^2 + 2\phi g\right]d\Omega \tag{6}$$

where:

Ω - considered area.

Both, the potential Φ and the source function g can be expressed by the triangular element (for 2D analysis). In that case:

$$\phi_e(x,y) = \sum_{i=1}^{3}\alpha_i\phi_{ei} \tag{7}$$

$$g_e(x,y) = \sum_{i=1}^{3}\alpha_i g_{ei} \tag{8}$$

where:

ϕ_{ei}, g_{ei} – values of functions ϕ_{ei} and g_{ei} in the nodal point i of the element e.

Knowing the functional equation for a single element

$$F(\phi_e) = \frac{1}{2}\sum_{i=1}^{3}\sum_{j=1}^{3}\phi_{ei}\phi_{ej}\iint\nabla\alpha_i\cdot\nabla\alpha_j d\Omega - \frac{k^2}{2}\sum_{i=1}^{3}\sum_{j=1}^{3}\phi_{ei}\phi_{ej}\iint\alpha_i\alpha_j d\Omega + \sum_{i=1}^{3}\sum_{j=1}^{3}\phi_{ei}g_{ej}\iint\alpha_i\alpha_j d\Omega = \frac{1}{2}[\Phi_e]^t[C^{(e)}][\Phi_e] - \frac{k^2}{2}[\Phi_e]^t[T^{(e)}][\Phi_e] + [\Phi_e]^t[T^{(e)}][G_e] \tag{9}$$

we can use them for all N elements in a selected region of solutions:

$$I(\phi) = \sum_{e=1}^{N} I(\phi_e) \tag{10}$$

Finally a solution to this particulair problem can by written as a matrix:

$$I(\Phi) = \frac{1}{2}[\Phi]^t[C][\Phi] - \frac{k^2}{2}[\Phi]^t[T][\Phi] + [\Phi]^t[T][G] \tag{11}$$

where:

$[\Phi] = [\phi_1, \phi_2, \ldots, \phi_N]^t$,

$[G] = [g_1, g_2, \ldots, g_N]^t$,

[C], [T] – global matrices containing corresponding local matrices $[C^{(e)}]$ and $[T^{(e)}]$.

When using FEM, it is important to choose appropriate element sizes. Elements dividing the selected area must be smaller than the shortest wave that may occur.

C. Finite Difference Time Domain Method

Finite difference time domain method was proposed by Kane Yee in 1966. FDTD is based on direct solution of Maxwell's equations. Therefore the implication of boundary conditions is the main problem.

Using the designation of the Yee cells (Fig. 1), Maxwell equations and saving them in a rectangular coordinate system (x, y, z) we get following equations [21]-[23]:

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} - \rho H_x\right) \tag{12}$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_z}{\partial z} - \frac{\partial E_x}{\partial y} - \rho H_y\right) \tag{13}$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} - \rho H_x\right) \tag{14}$$

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_z}{\partial z} - \frac{\partial H_y}{\partial y} - \sigma E_x\right) \tag{15}$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial y} - \sigma E_y\right) \tag{16}$$

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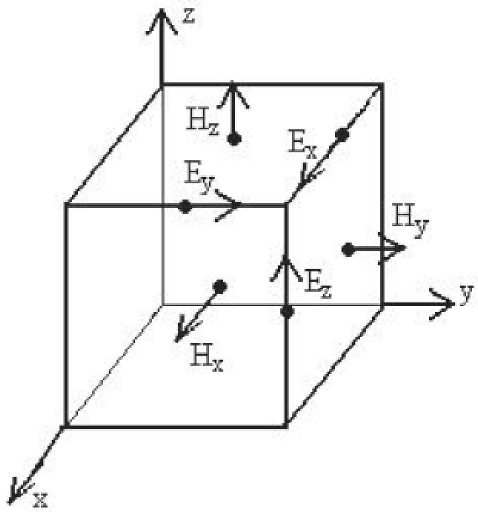

Fig. 1. Yee's cell

Using the notation introduced by Yee and marking the point in space as:

$$(i, j, k) = (i\delta, j\delta, k\delta) \tag{18}$$

and an arbitrary function describing the time and space in the following form

$$F^n(i, j, k) = F(i\delta, j\delta, k\delta, n\delta t) \tag{19}$$

where:

δ=δx=δy=δx – discretization step between consecutive points in space,

δt – time discretization step,

then the individual partial derivatives of function *F* can be written in the form of finite differences:

$$\frac{\partial F^n(i, j, k)}{\partial x} = \\ = \frac{F^n\left(i + \frac{1}{2}, j, k\right) - F^n\left(i - \frac{1}{2}, j, k\right)}{\delta} + 0(\delta^2) \tag{20}$$

$$\frac{\partial F^n(i, j, k)}{\partial t} = \\ = \frac{F^{n+1/2}(i, j, k) - F^{n-1/2}(i, j, k)}{\delta t} + 0(\delta t^2) \tag{21}$$

The determination of the individual components of the electric and magnetic fields is based on presented equations. Assuming that we know the value of such components of the magnetic field in the *n-th* moment of time and the value of the electric component at the time *n-1/2*, the only unknowns that remain in the calculation are the electrical components in the moments of *n* and *n+1/2*. The next step is to find the electrical component based on the values from previous step, and magnetic field values appointed for the half time step earlier (*n-1/2*).
All presented above numerical methods were implemented in many applications that allow to make EMF analysis.

Numerical Methods In Accuracy Improvement In Exposure System

One of the most important problem in bioelectromagnetics studies is accuracy one. Bioelectromagnetic research is one of the least accurate and difficult to perform. In many cases the tests are performed when the EMF exposure is significantly different from the one to which objects are exposed to in real life. Estimates made by the author show that due to interaction between the tested objects and the exposure system and among objects themselves, errors may exceed even 100% [24]. These phenomena are the reason for significant differences in the results of research done in different research centres. Most bioelectromagnetic studies are dealing with basic principles. This means that the most important factor is the correlation of research conducted in the laboratory with the influence of EMF on the objects in real life, which typically resemble conditions of free space. It all points to the need of reinterpreting the results of biomedical research and detailed analysis of the subject.
Placing any object with conductivity different than zero in the EMF causes certain losses. If the values of the electric field intensity and conduction current density are known, then the power loss that is absorbed by the objects is described by the formula

$$P_{abs} = \int_V EJdV \tag{22}$$

where:

P_{abs} – absorbed power,

E – electric field density vector,

J – current density vector,
V – volume of the object.

Substituting

$$J = \sigma E \tag{23}$$

and making simple transformations, we get the power absorbed by an object placed in the EMF, given by

$$P_{abs} = \sigma \int_V |E|^2 dV \tag{24}$$

A number of models were used for analysis and computer simulation with methods FEM and FDTD of interaction between the object and the exposure system. In this paper results for block model of a man are presented (Fig. 2). This model consists of a cube with 10cm long sides. Its electrical parameters equal ε = 80, σ = 0.84 S/m Dimensions of the conductive plates are 5 x 5 m.

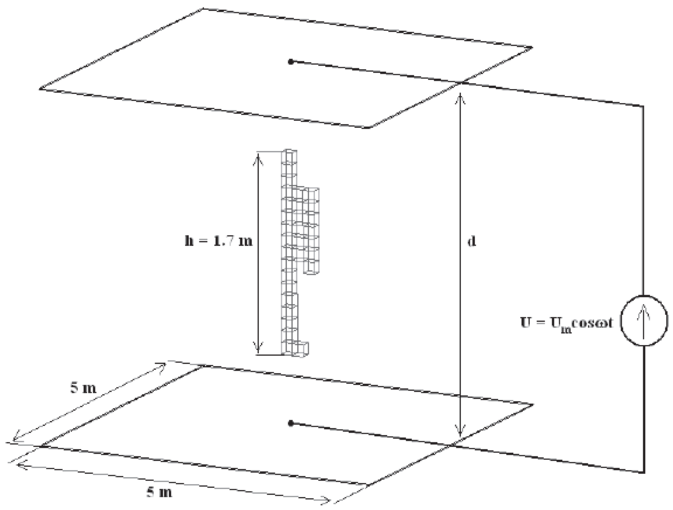

Fig. 2. A block model of a human in the TEM line

Simulations were performed for horizontal and vertical alignment of the model against metal plates. The line kept constant electric field of *E = 1 V/m*. After each time the plates were moved away (growth of *d/h* ratio) the voltage applied to the system was increased and the power absorbed by the object was calculated.

Results And Discussion

It may be noticed that the size of the exposure system has a significant impact on the electric field distribution inside the tested object (Fig. 3). The field distribution shows that the field strength in the facility is greater when the plates are near the line of the test model, than if the plates are further away. Greatest intensity occurs in the hand and legs of the model, and on its outskirts you can see significant disturbances of the electric field.

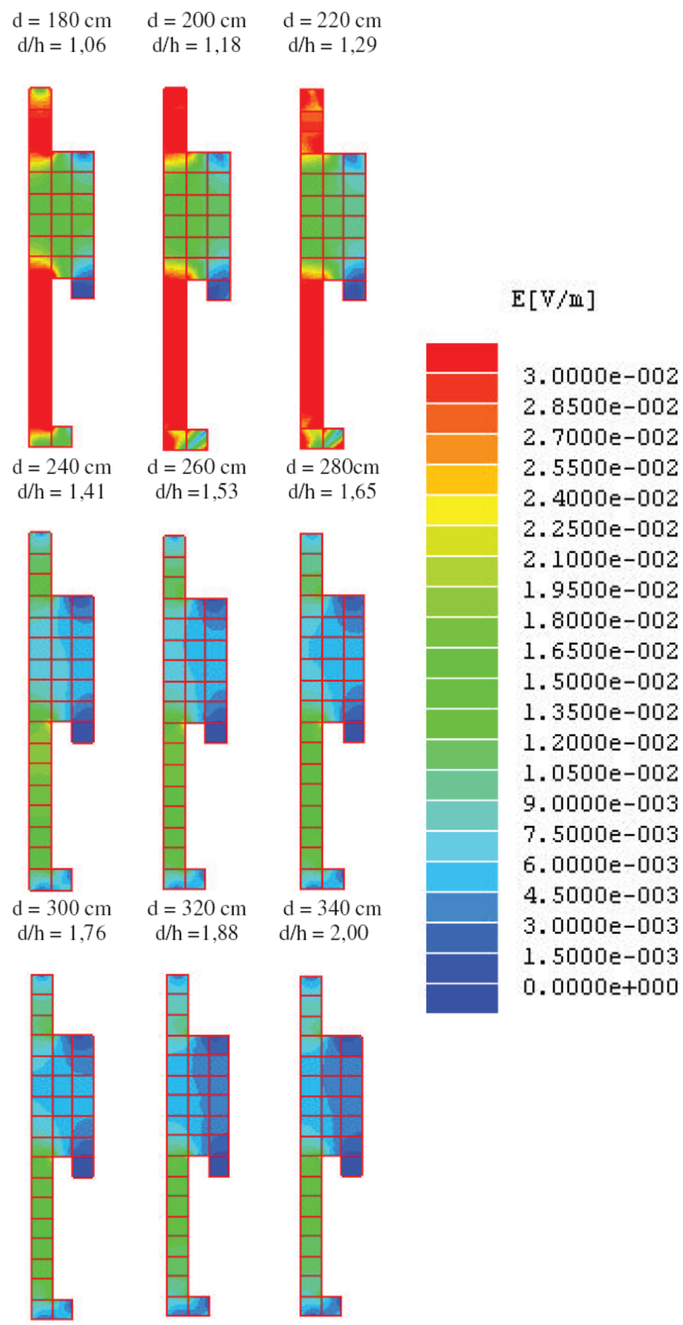

Fig. 3. Distribution of electric field inside a block model of a human placed perpendicular to the walls of the line for various distances between the plates, at a frequency f = 10 MHz

The results of changes in the power absorption as a function of the exposure and system's size are shown in Fig. 4. It is worth mentioning that when the plates of TEM line are close to the object the power absorbed is 30 times higher compared to the conditions of free space. Increase in the *d/h* ratio causes the absorbed power to decrease and approach asymptotically the value of absorbed power in free space, where the presence of metal plates is negligible. This condition is met for *d/h* ≈ 2.

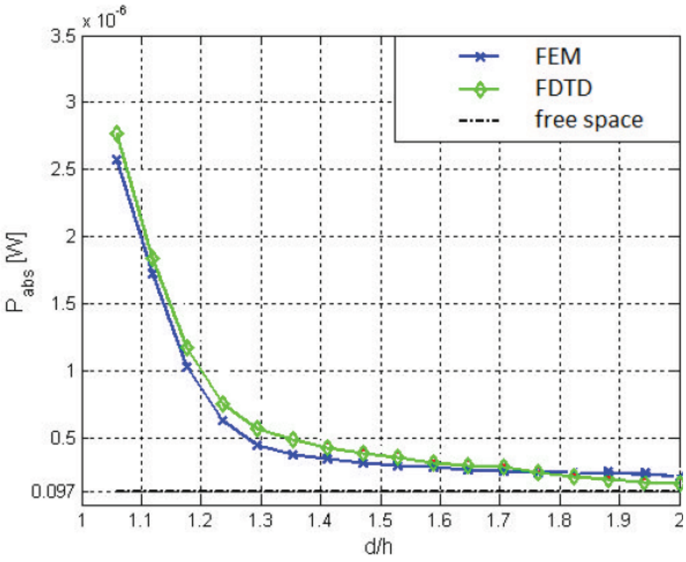

Fig. 4. The results of calculations of absorbed power by the block model of a human placed perpendicular to the plates of the walls

Conclusion

The most important feature and the biggest advantage of computer simulations using numerical methods is their ability to predict the behavior of the actual object based on its mathematical model. It is much easier and faster to perform computer simulations, rather than perform the measurements in real life conditions. Computer simulations are also extremely useful when the experiments are too dangerous to perform, i.e.: when the researched EMF can cause health issues or death of tested objects. Major drawbacks of computer simulations are restraints of computing resources and long duration of the calculations.

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