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STENTS IN ELECTROMAGNETIC FIELD

Abstract
The article presents results of investigation on interaction between stents and a magnetic component of an electromagnetic field. Stents are usually manufactured with specific materials, such as nickel-titanium alloy. Stent structure is defined by tens of closed contours, penetrated by the magnetic flux. Given the magnetic component changes in time, the passing of a magnetic flux induces the electric field in the branches of a stent, which then leads to the flow of an electric current. The authors present a numerical model that can be used to simulate the distribution of a magnetic field in a closest proximity of a stent, as well as to determine the branch currents values.

Keywords
stents, electromagnetic field, numerical model, induction, simulations

1. INTRODUCTION

The influence of the electromagnetic field on living orgasms has been known for years. Since 1987, stents have been used in medicine, and thus it is necessary to fully understand how they can affect human body [1]. The article presents results of the investigation on the interaction between stents and a magnetic component of an electromagnetic field. Stents are commonly used in treating various diseases. Depending on the localization in the human body stents can support the structure or prevent clogging of blood vessels, trachea, oesophagus or urethra. Stents are usually manufactured with specific materials, such as nickel-titanium alloy [2]. Stent structure is defined by tens of closed contours, penetrated by the magnetic flux [3, 4]. Given the magnetic component changes in time, the passing of a magnetic flux induces the electric field in the branches of a stent, which then leads to the flow of an electric current [5]. The authors present a numerical model that can be used to simulate the distribution of the magnetic field in a closest proximity of a stent, as well as to determine branch currents values. The results are compared with a custom-made physical model of the magnetic field generator and a custom-made stent. In the second part of the work authors present the results of

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the magnetic field interaction analysis for various frequencies and values of magnetic flux density, and stent meshes.

2. THE MODELS

The following subchapters present the developed models together with the corresponding results.

2.1. MATHEMATICAL MODEL

To avoid complicated three-dimensional field calculations, it is necessary for a model to be presented in two different ways. Firstly, it will be presented as an electric circuit, represented by the grid of resistive elements. Magnetic couplings (related to both magnetic field applicator and branches of the stent) will be modelled as voltage sources controlled by corresponding branch currents. Secondly, stent will be presented as an object located in space, with all branches assumed to be infinitely thin wires. This approach will be necessary to determine mutual inductances between branches and the outer source of magnetic field (applicator) [6]. In this part of the model the magnetic flux density will be determined for the purpose of verification of the model. The basic method for solving the circuit model is the modified node voltages method and Kirchhoff's current law [7]. Figure 1 presents the simple stent circuit.

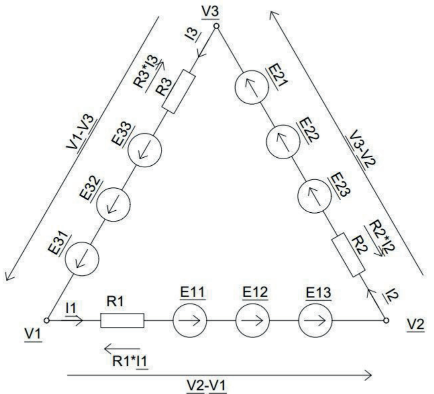

Fig. 1. Schematic of a simple stent-like structure

The equation below presents the modified node voltages method:

$$\underline{V}_k - \underline{V}_l = \underline{I}_i \cdot R_i - \sum_i \underline{E}_{ij} \tag{1}$$

where:

$\underline{V}_k, \underline{V}_l$ – potential of the k^{th} and l^{th} node,
$\underline{I}_i$ – current of the i^{th} branch spanning between the k^{th} and l^{th} node,
R_i – resistance of the i^{th} branch,
$\underline{E}_{ij}$ – forcing on the i^{th} branch caused by the current flowing through the j^{th} branch.

As mentioned before magnetic coupling is modelled as voltage sources controlled by corresponding branch currents:

$$\underline{E_{ij}} = j\omega M_{ij} \underline{I_j} \tag{2}$$

where:

$\underline{E_{ij}}$ – forcing on the i^{th} branch caused by the current flowing through the j^{th} branch,

$\underline{I_j}$ – current flowing through the j^{th} branch,

M_{ij} – magnetic coupling between i^{th} and j^{th} branch,

ω – angular frequency.

For field approach Biot–Savart law [8] is used for determining the magnetic flux density vectors, but the key operation is to determine the mutual inductances between two wires, as presented by the Formula (3) [3].

$$\mathrm{d}M_{ij} = \frac{\mu}{4\pi} \frac{\mathrm{d}\bar{l}_i \mathrm{d}\bar{l}_j}{r} \tag{3}$$

where:

M_{ij} – magnetic coupling between i^{th} and j^{th} branch,

$\bar{l}_i, \bar{l}_j$ – i^{th} and j^{th} branch curves,

r – distance between i^{th} and j^{th} branches,

μ – magnetic permeability.

2.2. NUMERICAL MODEL AND PROGRAM REALIZATION

For the purposes of the numerical model the applicator of the magnetic field is assumed to be a coil, described as a set of subsequent points in space. Contrary to the coil, description of a stent will require not only a geometrical description, but also description of a circuit structure of the stent i.e. data (provided during describing the stent or generated automatically from the geometrical set of coordinates of every branch) describing how the branches are connected to each other and where the nodes are located. Program developed for the purpose of performing numerical calculations features a partial automation of the stent creation. After providing geometrical points describing the stent in space, program automatically generates the description of a structure for the purpose of the circuit analysis. Every branch of the stent is geometrically described in a similar fashion as the coil.

2.3. VERIFICATION OF THE NUMERICAL MODEL

During the initial phase of the real model development the authors came to the conclusion that it might be impossible to achieve measurable values of potential or current. Thus, the verification will be also based on the comparison of the magnetic flux density vectors. The real model was produced as a copper wire winded on a PVC pipes. Despite the fact that copper is not normally used for stent production, it has been chosen due to the low cost and availability. The magnetic flux density meter was designed and assembled, using Arduino microprocessor. The main measuring component is the three-axis magnetic flux density meter MAG3110. Figure 2 presents the physical model. As predicted by the simulation, the highest value of the induced voltage was around 2.5 mV and thus unmeasurable by the available equipment (although the slight waveform of the used frequency was recognizable under the noise). The measurements of the magnetic flux density were taken in the proximity of the applicator. Comparison of measured and simulated data is presented on Figure 3. Black vectors present simulated magnetic field and red ones – measured. The stronger the field, the more accurate the measurements are (maximum measurable value declared by the producer is 1000 μT and the measurements were taken so that the highest measured value reached this threshold). Based on the verification, it might be assumed that the model is correct and the differences are caused by the measurement errors.

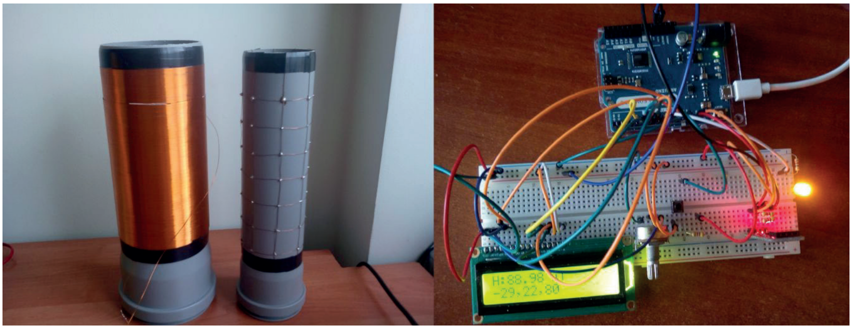

Fig. 2. Real model and measurement system

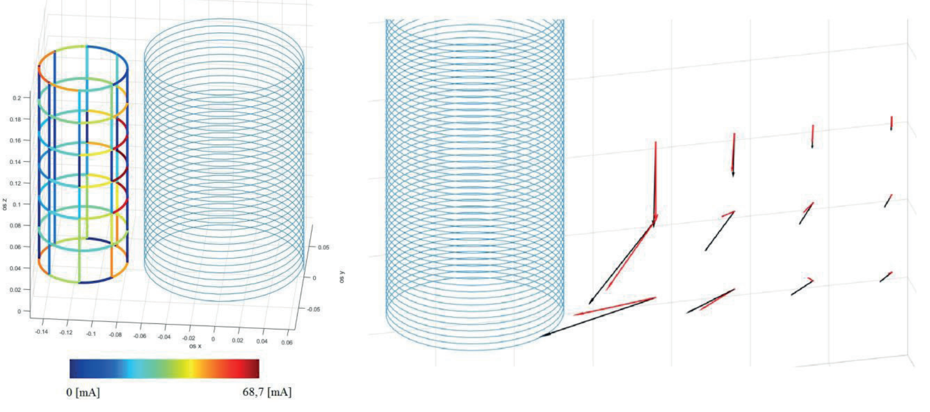

Fig. 3. Comparison of measured and simulated data of MF

2.4. PARAMETERS IN THE NUMERICAL ANALYSIS

Limit values of the magnetic field acknowledged by the ICNIRP (International Commission on Non-Ionizing Radiation Protection) are defined for certain frequencies. Those values are presented in Table 1. Thus, it is necessary to evaluate the influence of magnetic field on stents following these guidelines [2, 6, 9]

Table 1. Permissible MF limits in public places

Frequency range	Intensity of the component magnetic H [A/m]	Magnetic induction B [T]
1–8 Hz	$3.2 \cdot 10^4/f^2$	$4 \cdot 10^{-2}/f^2$
8–25 Hz	$4 \cdot 10^4/f$	$5 \cdot 10^{-3}/f$
25–400 Hz	$1.6 \cdot 10^2$	$2 \cdot 10^{-4}$
0.4–3 kHz	$3.2 \cdot 10^4/f^2$	$8 \cdot 10^{-2}/f$
0.003–10 MHz	21	$2.7 \cdot 10^{-5}$

f – signal frequency

For the analysis mesh stents were used. Stents are most commonly manufactured from surgical stainless steel – chromium-nickel-molybdenum alloy [10]. This material is characterized by corrosion resistance, necessary mechanical properties, non-toxicity and proper electromagnetic compatibility. In analysis parameters characterizing this material were used. The assessment of the influence of magnetic field on stents will include: various physical dimensions, frequencies and values of the flux density [11].

2.5. SIMULATION RESULTS

Simulation was carried out using the developed numerical model. For the analysis three different structures (meshes) were used: triangular, rectangular and rhomboidal. The uniform magnetic field was applied. A maximum value of induced current was chosen as an assessment parameter. Stents were situated in parallel to the vectors of the field. Figures 4–6 present the dependency between the stent's dimensions, EM field frequency and maximum induced current for above-mentioned topologies. Figure 7 presents the induced current values for above-mentioned topologies.

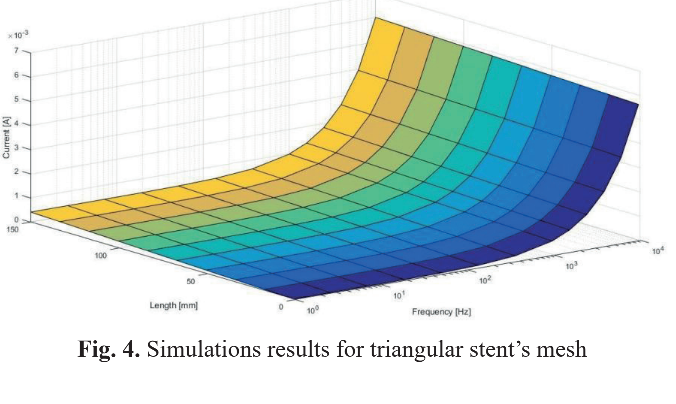

Fig. 4. Simulations results for triangular stent's mesh

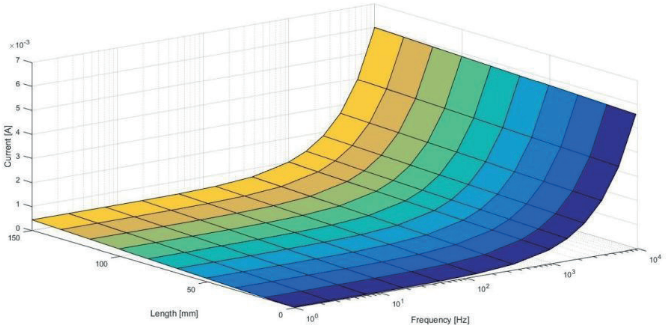

Fig. 5. Simulations results for rectangular stent's mesh

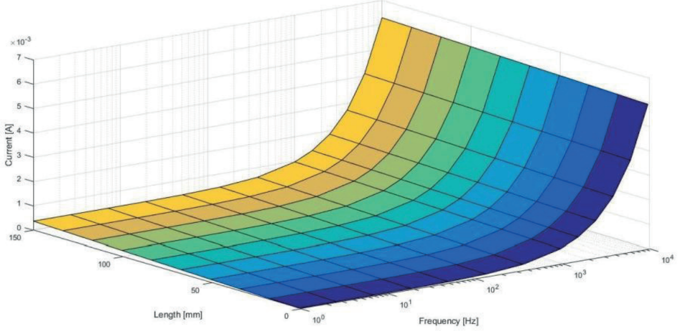

Fig. 6. Simulations results for rhomboidal stent's mesh

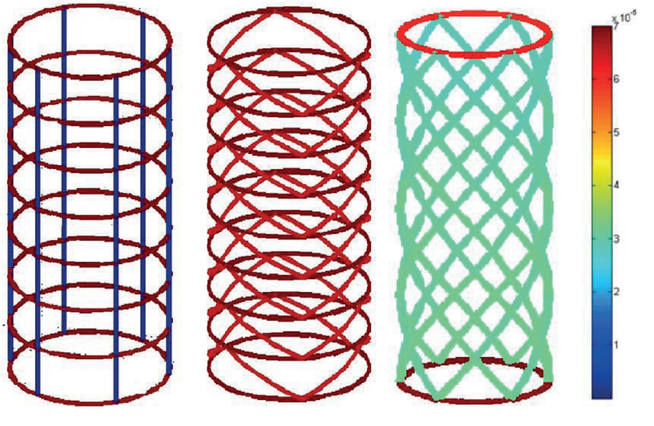

Fig. 7. Comparison of the values of induced currents on the spatial structure of stents (4 Hz)

3. CONCLUSIONS

To summarize, a reliable numerical model for determining the influence of the magnetic component of the electromagnetic field on stents was proposed and verified using the custom-made macroscale real model. The distribution of currents varies in accordance to the stent positioning in regard to the magnetic field vectors, thus it is possible to determine the case with most unfavourable distribution. For the limit values of the magnetic field induced branch currents values are low (10^{-3}–10^{-5} [A]), thus the dissipated power does not cause a severe thermal effect on human body parts. Dissipated power values span from nanowatts (for low frequency field) to single milliwatts (for the high frequency field).

Another conclusion is that the stent geometrical structure has a negligibly small influence on the total maximum branch current value (although it affects the distribution). Increasing the stent size for the same mesh structure increases the value of the current for the same branch. Because the branch resistances are 2–3 orders of magnitude higher than the reactances of mutual inductances, it might by assumed for simplicity that the dependence is linear. Taking into account that the stent size is heavily affected by its location in human body, the highest current can be measured in oesophagus located stents and it is one order of magnitude higher than for other locations.

Summarizing the entire analysis, it might be concluded that in public locations there is no possibility of harmful interactions for the stent using patients. There is possibility of harmful effects in case that the limit values are exceeded, especially by the high frequency magnetic field. It is also necessary to mention that stents were investigated “in vitro” and not in the environment of surrounding biological tissues. It is a viable simplification, because the conductance of the human tissues is much lower than the conductance of used alloy.

As a continuation of the research, different stent positioning in accordance to the magnetic field vectors or the density of the mesh effect on branch current values should be investigated.

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