Quality Festival 2019
ISSN 2620-2832

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FERROMAGNETICS IN MAGNETIC RESONANCE IMAGING

Abstract: *Useful tool in diagnostic radiology is magnetic resonance imaging (MRI). Scanning with this system can cause interaction between ferromagnetic used for creation of implants and magnetic fields of MRI. In order to determine magnetic field distribution the integral equation governing magnetic scalar potential is formed with induced magnetic charges on the thin arbitrary shaped ferromagnetic plate as unknowns. The obtained integral equations will be numerically solved using Equivalent electrodes method. Application of ferromagnetic materials in biomedical implants will be observed. Also, possible risk of interaction of these implants and MRI devices is analyzed.*

Keywords: *MRI, Ferromagnetics, External magnetic field, Equivalent electrodes method, Biomedical implants*

1. Introduction

Magnetic resonance imaging (MRI) can be found as safer system than those including X-rays, due to absence of ionizing radiation. However, there are three characteristics of MR that must be taken into account as potential injury causes: the strong static magnetic field including its spatial gradient, the pulsed gradient magnetic fields and the pulsed radiofrequency fields (Dempsey, 2002). Interaction of these fields with patient body is harmless if there are no ferromagnetic objects placed inside the body. But, if a patient has some biomedical implant, or he doubts that he could have some metallic foreign body, hazards are inevitable.

The strength of the static and gradient magnetic fields, as well as relative degree of ferromagnetism of the foreign body implanted and its location and length of time it has been in place are factors that influence the risk of injury during MRI.

Equivalent electrodes method is a numerical method for approximate solving of non-dynamic electromagnetic fields and other potential fields of theoretical physics. In recent years, this method became popular in computational electromagnetics problem solving (Veličković, 1996, Češelkoska, 2004, Veličković, 1998, Raičević, 2010).

One of possible application of ferromagnetic plates is as biomedical implants. A significant risk to some patients undergoing Magnetic resonance imaging (MRI) is the way implanted or internal ferromagnetic material can react to the strong magnetic field and RF impulses. When implanted ferromagnetic material is exposed to the magnetic field, it can be subjected to torque and translational forces strong enough to tear surrounding tissues. MR compatibility of these devices must be demonstrated by manufacturer's declaration (Harrington, 1968).

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2. Equivalent Electrodes Method

Let an ideal ferromagnetic body ($\mu \to \infty$) be placed in the external static magnetic field. $H_0 = -\mathrm{grad}\varphi$, where $\varphi = \varphi(r)$ is the exiting magnetic scalar potential, Figure 1. Then the total magnetic scalar potential,

$$\varphi = \varphi_p + \varphi \qquad (1)$$

satisfies Laplace's equation, $\Delta\varphi = 0$, and boundary condition $\varphi = C^{te}$ or $\hat{n} \times H = 0$ on the body surface, S. $\hat{n}$ is unit vector normal to the body surface, $H = -\mathrm{grad}\varphi$, is the total magnetic field strength and φ_p denotes the perturbed component of the magnetic scalar potential, which can be expressed as

$$\varphi_p = \oiint_S \eta(r') G(r, r') \mathrm{d}S \qquad (2)$$

where η defines the unknown induced magnetic charge surface density of the body surface and $G(r, r')$ is the corresponding Green's function.

For example, Green's function of single point magnetic charge placed in the point having radius vector r' is

$$G(r, r') = \frac{1}{4\pi |r - r'|} \qquad (3)$$

Using boundary condition $\varphi = C^{te}$ on the body surface, $r - r_0$, the following integral equation governing the surface charge density distribution can be formed:

$$\varphi + \oint_S \eta(r') G(r_0, r') \mathrm{d}S' = C^{te} \qquad (4)$$

The condition that the total magnetic charge of the body surface is always equal to zero,

$$\oint_S \eta(r') \mathrm{d}S' = 0 \qquad (5)$$

must be added to the integral equation (4).

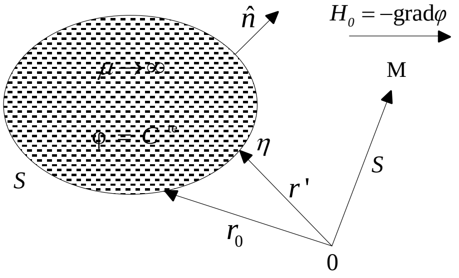

Figure 1. Ideal ferromagnetic body in an external magnetic field

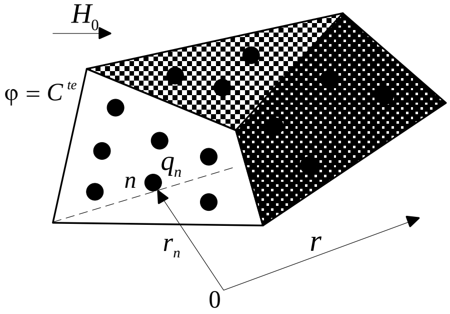

Figure 2. Application of EEM

Although an exact solution of the integral equation (4) does not exist in the general case of arbitrary shaped bodies, some numerical method can be used for solving this problem approximatively. Then is very useful the moment method (Dempsey, 2002). In the moment method application the numerical integration is always present, which produces some problems in the numerical solving of nonelementar integrals having singular or quasi-singular subintegral functions.

The application of EEM is more convenient, because the numerical integration is not necessary. In the case of three dimensional ferromagnetic bodies the equivalent electrodes are small perfect ferromagnetic spheres having equivalent radius determined in respect to the electrode surface elements which they substitute, Figure 2. Now the perturbed component of the magnetic scalar potential (2) can be approximatively expressed as

$$\varphi_{\mathrm{p}} = \sum_{n=1}^{N} q_n G(r, r_n) \qquad (6)$$

where:

r is the field point radius vector, r_n is the radius vector of the electrical middle point of the body surface element, or of the EE and $q_n,\ n = 1, 2, ..., N$ are the unknown magnetic charges of the EE governing the condition (5) in the following form:

$$\sum_{n=1}^{N} q_n = 0 \qquad (7)$$

N is the total number of the EE.

So the resulting magnetic scalar potential is:

$$\varphi = \varphi + \sum_{n=1}^{N} q_n G(r, r_n) \qquad (8)$$

In order to determine the unknown magnetic charges of the EE the following linear equations systern, governing boundary condition on the electrode surface, can be put

$$\varphi(r_m) + \sum_{n=1}^{N} \frac{q_n}{4\pi\sqrt{|r_n - r_m|^2 + a_{em}^2 \delta_{mn}}} = C^{te} \qquad (9)$$

$$m = 1, 2, \ldots, N$$

where a_{en} denotes the EE equivalent radius and δ_{mn} is Kronecker's symbol.

For example, the thin rectangular plate with sides $a, b, c << a, b$ in homogeneous external magnetic field, $H_0 = H_0 \hat{x}$, will be treated. Because of the existing symmetry the EE are placed only in the region $x > 0$ and $y > 0$, as Figure 3 shows. The approximative value of magnetic scalar potential is

$$\phi = -H_0 x + \sum_{n=1}^{N} \frac{q_n}{4\pi} \left(\frac{1}{R_1} + \frac{1}{R_2} - \frac{1}{R_3} - \frac{1}{R_4} \right) \qquad (10)$$

where:

$$\begin{aligned} R_1 &= \sqrt{(x - x_n)^2 + (y - y_n)^2}, \\ R_2 &= \sqrt{(x - x_n)^2 + (y + y_n)^2}, \\ R_3 &= \sqrt{(x + x_n)^2 + (y - y_n)^2}, \\ R_4 &= \sqrt{(x + x_n)^2 + (y + y_n)^2}. \end{aligned} \qquad (11)$$

In order to determine the unknown magnetic charge the zero value of the potential of the plate is realized.

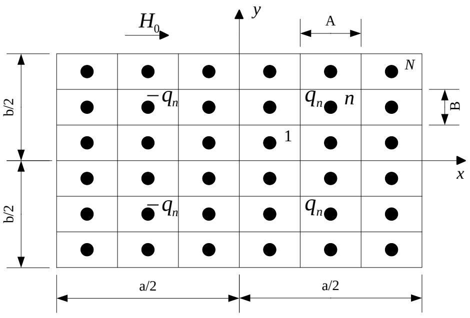

Figure 3. Thin square plate in homogeneous external magnetic field

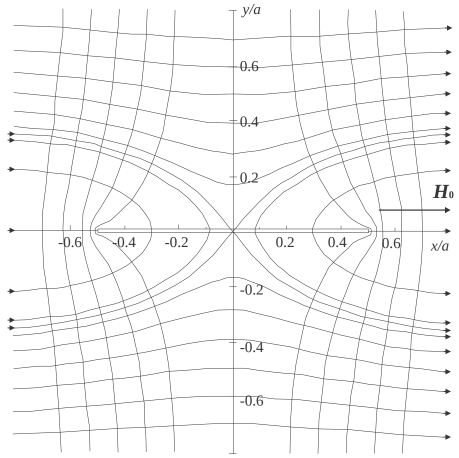

Figure 4. Equipotential lines and lines force of thin square plate in homogeneous external magnetic field

The EE are small spheres replacing the rectangular elements with sides A and B. The equivalent radius is determined using EEM (Veličković, 1996) with the following approximative formula

$$\frac{A_e}{A} = \begin{cases} 0.373\left(B/A\right)^{0.3882}, & 0.5A < B \le A \\ 0.404\left(B/A\right)^{0.5}, & 0.3A < B \le 0.5A \\ 0.696\left(B/A\right)^{0.957}, & 0 < B \le 0.3A \end{cases} \quad (12)$$

For example, in the Figure 4 are shown equipotential lines and lines force of thin square plate in homogeneous external magnetic field, $H_0 = H_0\hat{x}$. The plate with sides having length a is placed in plane $y = 0$, so it is $|x| \le a/2$ and $|z| \le a/2$.

The formula (12) gives the value $A_e = 0.373A$ for equivalent radius of thin square plate with sides A. Using moment method (Dempsey, 2002), the equivalent radius of thin square plate with side A is $A_e = 0.37A$, which agrees very well with the presented results.

If the thickness of the square plate is not neglectable and the external magnetic field is homogeneous, $H_0 = H_0\hat{z}$, Figure 5 shows the equipotential lines and lines force.

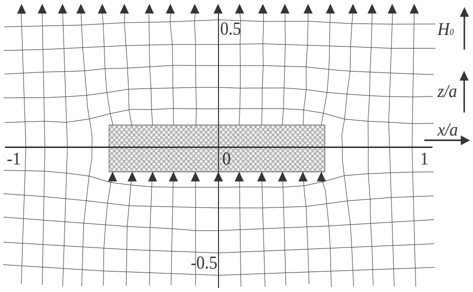

Figure 5. Equipotential lines and lines force of square plate in homogeneous magnetic field, for $a = b = 10c$

3. Magnetic resonance effects

Bioimplants are used in dentistry, orthopedics, plastic and reconstructive surgery, ophthalmology, cardiovascular surgery, neurosurgery, immunology, histopathology, experimental surgery, and veterinary medicine. Various classes of materials such as metals, alloys, polymers ceramics and composites have been widely used to fabricate the bioimplants (Manivasagam, 2010).

Metals that are currently being used as biomaterials are gold (Au), cobalt-chromium (CoCr) alloys, type 316 stainless steel, titanium (Ti), titanium-nickel alloys (TiNi - Nitinol) and silver-mercury alloys (AgHg). These metals are chosen based on their material properties and biocompatibility.

Many factors have to be considered before any particular material can be chosen, fabricated and used as a biomedical material.

3.1 Ortopedic implants

Ortopedic implants are mainly fabricated by nonferromagnetic or weakly magnetic matherials, thus they are acceptable for patients going through MRI. Here we can list joint prostheses, plates, screws, shunts, drains, etc. (Dempsey, 2002) But, some of orthopedic implants, especially ones with external fixation systems, including specially designed frames, clamps, rods, pins, posts, fasteners, wire fixations, connecting bars, screws, and other components used in orthopedic and reconstructive surgery, are made from ferromagnetics and they raise the concern of injuries.

The presence of a metallic implant in a patient or individual in the magnetic resonance (MR) environment may create a hazardous situation primarily due to excessive magnetic field interactions (Shellock, 2002). The MR environment may be unsafe for patients or individuals with certain biomedical implants or devices, primarily due to movement or dislodgment of objects made from ferromagnetic materials (Shellock, 2002).

4. MRI safety

It is very important to have information about structure of orthopedic implants before starting of MRI, in order to avoid potential injuries, or in worst case, death of patient. Most orthopedic implants are safe for patients undergoing MRI. External fixator clamps, however, exhibited significant ferromagnetism, as the bolts are highly ferromagnetic. Nonimplant stainless steel devices may be magnetic.(Kumar, 2010) For example, Perfix interference screw used for reconstruction of the anterior cruciate ligament has been found as highly ferromagnetic. It is embedded in bone, so it has sufficient force to prevent movement. On the other hand, it causes significant signal distortion during MRI of the knee (Shellock, 1992).

Big concern is also heating, due to good conductivity of materials, especially in external fixation systems. Safety of scanning patients with external fixation systems is on low level, and thus it has to be detailed procedure of scanning, evaluated on a case-by-case study. If one uses procedure different from evaluated for its fixation device, scanning will end with hazard.

5. Conclusion

In order to determine magnetic field distribution by the side of thin ferromagnetic plates in the external magnetic field the EEM is used. Then integral equation governing magnetic scalar potential is adopted with induced magnetic charges on the plate surface as unknowns. The method is very useful in practice. Thin ferromagnetic plates in the external magnetic field can be observed like biomedical implants in presence of medical devices (MRI scanner), in sence of MR compatibility, giving good reference for production of implants and procedures for safe MR scanning.

Acknowledgment: This paper is part of project III41017 Virtual human osteoarticular system and its application in preclinical and clinical practice, funded by the Ministry of Education and Science of Republic of Serbia, (http://vihos.masfak.ni.ac.rs).

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