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Quasi-static multi-domain inverse boundary element method for MRI coil design with minimum induced E-field

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ABSTRACT

Boundary element methods represent a valuable approach for designing MRI gradient coils. The temporally varying magnetic fields produced by gradient coils induce electric currents in conducting tissues and so the exposure of human subjects to these magnetic fields has become a safety concern, especially with the increase in the strength of the field gradients used in MRI. Here we extend the boundary element method presented in Cobos Sanchez et al. (2010) [4], for the design of coils that minimize the electric field induced in prescribed multi-compartment volume conductor made of different homogeneous sub-domains. The multi-domain E-coil method is illustrated with the design of cylindrical head gradient coils, whose performance is numerically compared to that produced by conventional coils and single domain E-coils.

1. Introduction

Magnetic resonance imaging (MRI) is a non-invasive technique, that relies on the principles of nuclear magnetic resonance (NMR), and is used for imaging the inside the human body. MRI is based on the use of well defined and controlled magnetic fields, such as the magnetic field gradients, used to encode spatially the signals from the sample. These field gradients are generated by coils of wire, usually placed on cylindrical surfaces, although other geometries can be employed [16].

The problem in gradient coil design is to find optimal positions for the multiple windings of coils so as to produce fields with the desired spatial dependence and coil properties [16] (low inductance, high gradient to current ratio, minimal resistance, and good field gradient uniformity). Coil design is then an electromagnetic inverse problem which can be formulated in the magneto-static regime, and is often described as a constrained optimization problem. One of the most important requirements to consider when designing a coil is to minimize its interaction with any other equipment present in the MRI system. The switching on and off of gradient coils generates an undesired electric field in nearby conducting objects, producing eddy currents which not only occur in the scanner itself, but can also be induced in the conducting tissue of the patient, becoming then an important safety issue. These induced currents can lead to peripheral nerve stimulation (PNS) [14], a process that can be related to the depolarization of nerve or muscle cell membranes; being able to produce important bio-effects, including a feeling of a tingling or twitching, and at higher levels of stimulation, even pain. Some solutions have been proposed to overcome this safety problem in MRI, such as the work presented by Harvey and Katznelson [6] or Parker et al. [11].

Boundary element methods (BEMs) have been proved to be an excellent solution for electromagnetic inverse problems; precisely for coil design, where the concept of stream function is incorporated into a constant inverse boundary element method (IBEM) [12,9], to produce a powerful tool for the design of gradient coils with totally arbitrary geometry [13,10].

Recently Cobos Sanchez et al. [4] proposed the E-coil method, which is a quasi-static IBEM used to design novel gradient coils for MRI, in which the induced electric field is minimized, and thus reducing the likelihood of peripheral nerve stimulation. The E-coil method incorporates a new constraint in the coil design to minimize the modulus of the electric field over a defined uniform conducting region. The E-coil approach is described through the single domain version of an existing forward BEM approach for electromagnetic problems [3].

In this work, we present an extension of the E-coil method [4] to a multi-domain formulation, in order to provide a more realistic characterization of the regions where the E-field is desired to be minimized, that is, the human body. We develop a quasi-static IBEM which can be used for the design of coils that minimize the electric field induced in prescribed conducting regions made of different homogeneous sub-domains, as a representation of a heterogeneous system.

Section 2 reproduces a brief outline of the mathematical formalism of the stream function IBEM [12,9]. Subsequently a discrete characterization of the electric field in the multi-domain

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