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Non-invasive imaging of biological microstructures by VHF waves

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***Abstract*—The most of medical imaging methods involve ionizing waves and scanning of a wide human body area whether the area under investigation is large or not. In this paper, we propose a novel method to evaluate the shape of microstructures for application in the medical field, with a very low invasiveness for the patient. We focus our attention on the the tooth's root canal shape estimation, which is a crucial step in the endodontic procedures. The proposed method makes use of a flexible thin-wire antenna to be inserted into the tooth's root canal and radiating non-ionizing Very High Frequency (VHF) waves. By measuring the spatial distribution of the magnetic field in the neighboring of the tooth, it is possible to reconstruct the tooth's root canal shape by solving an inverse problem that involves the estimation of the shape of the antenna against the sensors panel. Simulation results show the validity and the robustness of the proposed approach.**

I. Introduction

The medical imaging methods involve electromagnetic waves in a frequency range that spans from some Hz to GHz and over. Many of these methods are characterized by their invasiveness since they involve both ionizing waves and the scanning of wide areas even when only a focused investigation is needed. In particular, in this paper we address the tooth's root canal shape reconstruction (Figure 1).

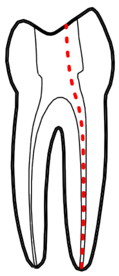

Fig. 1. Tooth's root canal path (point red line).

The solution of such a problem is of great interests in endodontic procedures where rotary instruments, named "files", are subjected to various types of mechanical stress. This stress is directly related to canal characteristics (i.e. angle, curvature radius, length, possible bifurcations) and modifies the instrument life and, consequently, its breakage [1]. Therefore, root canal reconstruction techniques have to be implemented. To this aim, as an alternative to established X-ray imaging, we propose a novel method that is straightforward and can be applied many times on the patient, because of its low invasiveness. The proposed method works with non-ionizing low-power electromagnetic waves, in the Very High Frequency (VHF) range, and makes use of a system endowed with a microtransmitter and a sensors panel to acquire the spatial distribution of the magnetic field. The magnetic field component is selected since the physical domain can be characterized with about uniform magnetic permeability in the VHF range.

The microtransmitter radiates the VHF waves by means of a flexible thin-wire microantenna, inserted in the root canal. Hence, the microantenna can be assumed to have the same shape of the analyzed structure. By measuring the spatial distribution of the magnetic field in the neighborhood of the thin-wire antenna, it is possible to reconstruct the microstructure image by solving an electromagnetic inverse problem.

II. Methodology

The thin-wire antenna is supposed to be made by a sequence of linear segments: given a model for the characterization of the magnetic field at a set of points in space (forward problem) and given a set of measurements at these points, it is possible to solve the inverse problem in terms of the distances of the antenna axis points from the sensor panel. The forward problem can be solved in the frequency domain through a numerical model based on the point-matching Method of Moments (MoM) [2], [3]. The Levenberg-Marquart algorithm can be used in solving the inverse problem by means of minimization of the Euclidean distance between the measured field and the field generated by a given configuration of thin-wire piecewise antenna [4].

The current distribution along the antenna is evaluated by solving an appropriate integral equation in frequency domain, derived from Maxwell's equations. In particular, by introducing the relevant electromagnetic quantities (i.e., scalar electric and vector magnetic potentials) as functions of the unknown currents, the following integral equation in frequency domain, holds [4]:

$$\begin{aligned} &-j\omega \int_L \vec{u}\cdot[\vec{u}'\int_\Omega \mu I_s(l')g(\vec{r},\vec{r}')dl']dl+ \\ &+\int_L \frac{\partial}{\partial l_{tg}}[\frac{1}{j\omega\dot{\epsilon}}\int_\Omega \frac{dI_s(l')}{dl'}g(\vec{r},\vec{r}')dl']dl = \dot{z}_s\int_L I_s(\vec{r})dl \end{aligned} \quad (1)$$

Equation (1) is a general relation that depends only on longitudinal current and on geometrical quantities related to the conductors constituting the thin-wire structures to be analyzed. In fact, I_s is the longitudinal current flowing into the conductor, supposed concentrated on its axis ($\vec{u}'$ as the unit vector) because of the thin-wire assumption [2], $\vec{u}$ is the unit vector tangential to the conductor's surface, as shown in Figure 2, $\dot{z}_s$ is the per-unit-length surface impedance of the conductor, Ω is the length of the exciting conductor, the subscript tg indicates the component tangential to the wire surface, L is the length of the induced conductor, $\vec{r}$ and $\vec{r}'$ are space position vectors of the observation and source points, respectively; $g(\vec{r},\vec{r}') = \frac{e^{-\dot{k}|\vec{r}-\vec{r}'|}}{4\pi|\vec{r}-\vec{r}'|}$ is the Green's function in an unbounded region. The quantity $\dot{\epsilon} = \epsilon + j\omega\sigma$ takes into account the complex medium permittivity and $\dot{k} = \sqrt{-\omega^2\mu\dot{\epsilon}}$ is the wave number.

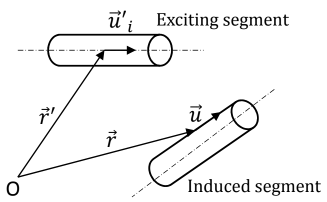

Fig. 2. General thin-wire geometric references.

The problem of finding the current distribution along the antenna, represented by equation (1), is numerically solved by splitting the thin-wire antenna into a finite number of linear segments. Once the currents are computed, the magnetic field components in the surrounding medium are given by the dipole theory, by superposing the effects of all segments [2].

III. Numerical Results

In order to validate the capabilities of the proposed method, numerical experiments concerning the shape estimation of a specific tooth's root canal have been carried out. A NiTi (electrical conductivity $1.1 \cdot 10^6$ S/m) thin-wire antenna, 0.1 mm in radius and 2.3 cm in length, is assumed to be inserted in a typical root canal and fed by a sinusoidal current source with frequency equal to 100 MHz and the amplitude equal to 50 mA. It has to be underlined that this current value, as well as the selected frequency, can be well tolerated by the human tissues also depending on the time of application (i.e., a few seconds) [5]–[7]. In order to approximate the characteristics of a tooth, the medium around the canal is assumed to have zero electrical conductivity, relative permittivity equal to 15 and relative permeability equal to 1 [8].

The measurements are supposed to be affected by additive white Gaussian noise: the measured values of magnetic field at sensors locations have been calculated by means of the MoM-based forward solver described in Section II and then the noise has been added.

Three different sensor panels has been tested, namely 24 or 32 sensors on two parallel flat panels and 32 sensors on a cylindrical panel. Moreover, in order to test the effect on reconstruction accuracy of an increasing number of variables involved in the optimization process, the shape of the antenna has been reconstructed by assuming a two branch conductor or a three branch conductor, alternatively: if one considers common canal shapes and curvatures, both of these configurations can satisfactorily represent the canal shape.

The behavior of the relative reconstruction error versus the SNR for different sensor panels and numbers of assumed antenna branches is shown in Figure 3.

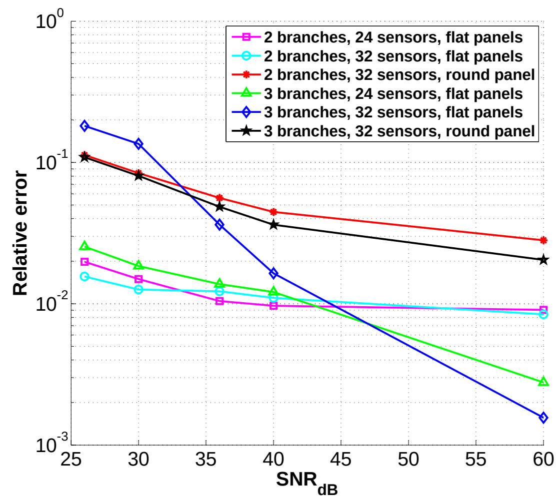

Fig. 3. Relative reconstruction error vs. SNR (dB).

Satisfactory accuracies has been achieved with all the configurations tested, even when the SNR is low. However, by approximating the antenna with a two branch conductor, a better robustness with respect to noise is observed. The prototype of the sensors panel and the related electronic equipment, is in progress.

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