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Radiofrequency magnetic resonance coils and communication antennas: Simulation and design strategies

Giulio Giovannetti [a,b,*], Gianluigi Tiberi [c,d]

[a] Institute of Clinical Physiology, National Council of Research, Pisa, Italy
[b] Fondazione G. Monasterio CNR - Regione Toscana, Pisa, Italy
[c] Laboratory of Medical Physics and Biotechnologies for Magnetic Resonance, IRCCS Stella Maris Foundation, Pisa, Italy
[d] Imago7 Foundation, Pisa, Italy

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ABSTRACT

Coils simulation and design is a fundamental task to maximize Signal-to-Noise Ratio in Magnetic Resonance applications. In the meantime, in the last years the issue of accurate communication antennas analysis has grown. Coil design techniques take advantage of computer simulations in dependence on the magnetic field wavelength and coil sizes. In particular, since at high frequencies coils start to behave as antennas, modern Magnetic Resonance coil development exploits numerical methods typically employed for antennas simulation.

This paper reviews coil and antenna performance parameters and focuses on the different simulation approaches in dependence on the near/far field zones and operating frequency.

1. Introduction

Magnetic Resonance Imaging (MRI) is a non-invasive diagnostic technique based on the phenomenon of Nuclear Magnetic Resonance (NMR), which employs the signal from protons for producing anatomic images. The basic physical principle is related to the behaviour of atomic nuclei with a magnetic moment, which when placed in a static magnetic field (B_0) precess about its direction at a specific frequency, named Larmor frequency. For examining the tissue characteristics, the nuclei in the static field are irradiated by a radiofrequency (RF) magnetic field (B_1) whose direction is perpendicular to B_0 field direction and whose frequency is equal to the Larmor frequency. The nuclear magnetization will make an excursion from the static field direction and induce a voltage in the receive coil as it returns to align with the static field. Tissue characteristics information is achieved by studying the atoms magnetic moment dynamics. In MR systems, the irradiated RF field and the transverse RF field are generated and picked up by transmit and receive coils, respectively [1]. The transmit coil has to produce a highly homogeneous alternating field in a wide field of view (FOV), since the extension of the region under investigation is not known a priori. For achieving this, transmit coils are usually large for optimizing the field homogeneity and including a significant tissue volume. The receive coil has to maximize signal detection while minimizing the noise, and for this purpose its dimensions have to be minimized [2]. For achieving an optimal signal reception over a large region, phased array coils have been introduced [3]. In such configuration, each coil element within the array picks up the signal from a specific tissue region while minimizing the interactions with the other coil elements. Finally, both transmit and receive coils must be adapted to the specific goal and to the sample sizes.

For optimizing RF coil performance for a given application, an accurate simulation and design process has to be performed. Current design techniques take advantage of computer simulations for preliminary testing different coil geometries.

Some coil characteristic, as magnetic field homogeneity, can be estimated by electromagnetic theory as Biot-Savart as long as the nearly static field assumption holds, but with the increase of static field intensity in modern scanners, this condition is rarely satisfied [4]. Moreover, when the coil is loaded with a sample, the distribution of Signal-to-Noise Ratio (SNR) is strongly affected by sample electromagnetic properties. For these reasons, modern MR coil development exploits numerical methods which permit to simulate the behaviour of the coil in presence of realistic loads and to investigate the coil efficiency at high frequency, when the coils start to behave as antennas. This review briefly describes coil and antenna performance parameters and their estimation methods.

2. Characterization of RF coils for MR

RF coils are designed as resonant structures and can be schematized by an equivalent *RLC* circuit whose current which flows on it is

* Corresponding author at: Via Moruzzi 1, 56124 S. Cataldo, Pisa, Italy.
E-mail address: giovannetti@ifc.cnr.it (G. Giovannetti).

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maximized at the Larmor frequency (Fig. 1). As according to the reciprocity theorem [5], V can be the voltage source (transmit coil) or the sample-induced voltage (receive coil). L is the system inductance which takes into account for the energy that can be stored in the magnetic field and it is related to the conductors size and geometry. C is the system capacitance and is mainly resulting from the contribution of discrete capacitors.

Energy exchange between magnetic (B) and electric (E) field might alternate in time with maximum efficiency at the resonant frequency. By applying Kirchhoff law, the circuit resonant frequency can be calculated as:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

The resistance R is the sum of all the resistances that can be associated to loss mechanism within the conductors and within the sample [6]. In particular:

$$R = R_{coil} + R_{sample} \quad (2)$$

R_{coil} takes into account for the losses within the coil conductors, depending on the conductor geometry, and includes radiative and tuning capacitors losses. R_{sample} are the sample losses caused by RF currents, induced by the fluctuating magnetic field, and by electric fields in the sample, mainly generated by the coil capacitors due to their dielectric media generating displacement currents [7].

The definition of the **coil quality factor**, expressed in terms of circuit parameters, provides a quantitative measure of circuit quality, as [1]:

$$Q = \frac{2\pi f_0 L}{R} = \frac{1}{R}\sqrt{\frac{L}{C}} \quad (3)$$

A common parameter of coil performance evaluation is the **ratio *r*** between the quality factor of empty resonator (Q_{empty}) and resonator with the sample (Q_{sample}) [8]:

$$r = \frac{Q_{empty}}{Q_{sample}} = 1 + \frac{R_{sample}}{R_{coil}} \quad (4)$$

An optimal coil design is a necessary constraint for minimizing the coil noise with respect to the sample noise and for providing maximum SNR, since $SNR\alpha\sqrt{1-\frac{1}{r}}$ [9].

The **coil sensitivity** is another important parameter that characterizes the RF coils performance. It is defined as the ratio between the magnetic field (B_1) induced by the RF coil at a given point and the total power delivered to the coil P ($P = 0.5^*R^*i^2$, where i is unit current), as follows [10]:

$$\eta = \frac{B_1}{\sqrt{P}} \quad (5)$$

The reciprocity theorem [5] allows to use Eq. (5) to characterize both the transmit and receive performance of a coil. It is important to note that maximizing the coil sensitivity will maximize also the SNR.

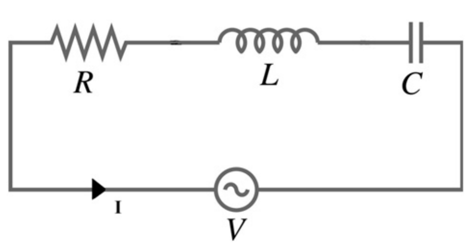

Fig. 1. RLC equivalent circuit of a radiofrequency coil.

3. Characterization of antennas for communication

An antenna, being a device for radiating or receiving radiowaves, needs currents and voltages on its structures to generate the required B- and E-fields that constitute an electromagnetic wave. The performance of an antenna are described by various parameters [10].

The power and the energy of the electromagnetic waves can be associated with the electromagnetic fields through the definition of the Poynting vector, which will be defined later.

The **radiation pattern** is a graphical representation of the spatial distribution of radiated energy in dependence on space coordinates. In particular, antenna performance are described in terms of its E-plane and B-plane patterns, which are usually referred to as "radiation lobes".

The **radiation intensity** in a given direction describes the power radiated from an antenna per unit solid angle and can be obtained by multiplying the radiation density (antenna power density associated with the electromagnetic fields) by the square of the distance.

The **directivity** indicates the radiation intensity in the direction of its strongest emission versus the radiation intensity emitted by an ideal isotropic radiator radiating the same total power.

The **gain** of an antenna is usually defined as the ratio between the radiation intensity in a given direction and the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically.

The **efficiency** of an antenna is the ratio of the power delivered to the antenna relative to the power radiated from the antenna. This parameter takes into account the losses at the input terminals and within the antenna structure: a high efficiency antenna will have most of the power present at the antenna input radiated away, while a low efficiency antenna will have most of the power absorbed as losses within the antenna, or reflected away due to impedance mismatch.

In a plane which contains the direction of the beam maximum, the **half-power beamwidth** (HPBW) indicates the angle between the two directions in which the radiation intensity is one-half (−3 dB) the maximum beam value. It describes the antenna resolution capabilities for distinguishing between two adjacent radiating sources.

The **polarization** of an antenna in a given direction describes the polarization of the wave radiated by the antenna (transmit antenna) or incident at the terminals (receive antenna), in terms of electric field orientation. Polarization can be classified as linear, circular or elliptical, in dependence on E-field components in terms of direction and magnitude.

Finally, for receive antenna an **equivalent length** or an **equivalent area** can be defined in dependence on antenna geometry, with the purpose to describe the antenna receiving characteristics in terms of capability to capture electromagnetic waves and to extract power from them.

4. Near field and far field

While an antenna has to emit an electromagnetic wave, the name "coil" derives from the working principle of RF coils in classic MR imaging, because it is based on the principle that currents will generate a B_1 field. And thanks to the reciprocity principle, elements that are designed to receive signals are also called coils. However, at high frequencies, coils begin to act as antennas [11].

High intensity B_1 field is present in a region close to the coil, the so-called "reactive field" region, that is associated with the classical desired coil resonance operation. In this region, the B-field generated by the currents in the coil is much greater than the E-fields that are generated in concomitance and only a small fraction of the B-field can be associated to the propagating wave. The major part of this B-field is associated to the reactive field, which causes a trapped energy near the coil without emissions to the surroundings. Being the coil a resonant structure, these fields are the coil resonant fields, which increase with increasing coil quality factor, which will be described later. This region is called the "near field" zone.