Performance of a petal resonator surface (PERES) coil via equivalent circuit simulation

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MRI coil parameters can be estimated via simulation using an equivalent RLC circuit to investigate coil performance. The Spice Opus simulator was used to simulate the loss return coefficients of a circular-shaped coil and a petal resonator surface (PERES) coil via equivalent (RLC) circuit. Simulated coefficient spectra were obtained and compared with experimentally-acquired spectra generated by both coils. From these spectra, resonant modes and quality factors of both coil prototypes were computed at 64 MHz and compared. Impedance and resonant frequency of the 8 petal-PERES coil design were computed and compared against those obtained with the circuit simulation. PERES coil design produced an impedance value of 54 Ω, and an experimental resonant frequency differing by less than 1% from that predicted by the circuit simulator. The quality factor of the coil prototype differs by only 8% from that obtained with the simulation method. Due to construction imperfections in the coil design, it showed a drop of 8.84 dB in attenuation compared with the simulation results obtained with the aid of an equivalent circuit. This scheme may serve as an alternative to the trial-and-error method usually used to develop dedicated RF coils for magnetic resonance imaging.

Keywords: Magnetic resonance imaging; RF coil; simulation; equivalent circuit; quality factor; resonator coil; RLC.

Los parámetros de una antena de IRM pueden ser estimados empleando un circuito equivalente RLC para estudiar su desempeño. Se empleó el simulador de circuitos Spice Opus para determinar los coeficientes de retorno por pérdida de una antena circular y la antena PERES haciendo uso de un circuito equivalente RLC. Se obtuvieron espectros de manera experimental y simulada de ambos prototipos de antenas, para propósitos de comparación. A partir de estos espectros se calcularon y compararon los modos de resonancia y los factores de calidad para una frecuencia de 64 MHz. Se calcularon la impedancia y la frecuencia de resonancia de una antena PERES con 8 pétalos, y se compararon con los datos obtenidos con la simulación. La antena PERES tiene una impedancia de 54 Ω y una frecuencia de resonancia que difiere en menos del 1% de la obtenida con la simulación. El factor de calidad del prototipo difiere únicamente en 8% del obtenido con el método de simulación. Debido a las imperfeciones resultantes de la construcción, el factor de calidad de la antena muestra una caída de 8.84 dB en la atenuación comparada con el valor obtenido con el circuito equivalente. El enfoque presentado puede convertirse en una alternativa al método de ensayo y error usualmente empleando para desarrollar antenas de RF para imagenología por resonancia magnética.

Descriptores: Imagenología por resonancia magnética; antenas RF; simulación; circuito equivalente; factor de calidad; antena resonador; RLC.

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1. Introduction

A combination of practical experience and theory is used to build magnetic resonance imaging (MRI) coils. The usual selection of the key coil parameters such as inductance (L) and capacitance (C) is critical to building coils with high performance. Most MRI coil development has been done following the trial-and-error approach. The simulation of an equivalent circuit to calculate the key parameters of a MRI coil provides us with a way to save time and effort [1-7]. The method is simple and also effective for RF coils operating at low frequencies. The Kirchhoff voltage and current laws are then employed to establish a set of linear equations, whose solution gives the resonant frequencies and the current distributions in the coil [8]. The exact solutions to Maxwell's equations represent a major problem for a number of coil configurations. Due to the difficulty encountered in solving Maxwell's equations, as a first step to studying the coil performance, it is suggested the equivalent-circuit approach be used. This is based on the evidence that Maxwell's equations can be solved via an equivalent circuit. It is well accepted that MRI coil characteristics can be simulated via a lumped-element network. This represents a first-approximation solution, but a more accurate analysis can be done via the method of moments which is a useful tool in the design of RF coils for MRI [9-12]. The Simulation Program with Integrated Circuits Emphasis (SPICE) is a good candidate for simulating the performance of coils for MRI applications. SPICE has been previously used to study the electrical properties of a volume RF coil [13].

The physical principles of a new surface coil design able to improve the signal-to-noise ratio (SNR) over the circular-shaped coil was first introduced by Mansfield in 1988 [14] and experimentally developed by Rodríguez *et al.* [15]. This coil design is called the Petal Resonator Surface (PERES) coil. Despite the fact that an SNR model is proposed by Mansfield, the trial-and-error approach was still used to build the very first version of this type of coil design, taking a considerable amount of effort and time. This is because no information on the capacitance and inductance values were previously provided in the literature. PERES coil has proven to have a better performance when compared with the circular-shaped coil for the cases of a) phased-array coils [16] and b) SENSE coils [17]. Other PERES coil designs have also been investigated [18]. Therefore, an analysis of its performance as a function of the electronic component values can be useful before any attempt to build a coil prototype is made. The equivalent-circuit method was applied to simulate the coil performance of circular-shaped coils, and PERES coils. Despite the limitations of the lumped-element approach, it can offer some useful information regarding the coil performance, and represents an advantage over the trial-and-error approach. Simulated return coefficient spectra were obtained via the equivalent circuit. Both circular-shaped and PERES coil prototypes were built, and their return-loss spectra were experimentally calculated and compared against the simulated spectra, respectively. Electrical characteristics of an 8 petal PERES coil design were first simulated with the SPICE programme to guide the coil construction. In addition, theoretical and experimental quality factors were compared for both coil prototypes.

2. Simulation program with integrated circuits emphasis

SPICE programme is a general-purpose circuit simulator with optimisation utilities for nonlinear dc, nonlinear transient, and linear ac analyses. This circuit analysis programme was developed at the Department of Electrical Engineering and Computer Sciences, University of California at Berkeley in the early 1970s. Circuits may contain resistors, capacitors, inductors, mutual inductors, independent voltage and current sources, four types of dependent sources, lossless and lossy transmission lines (two separate implementations), switches, uniform distributed RC lines, and the five most common semiconductor devices. SPICE is a standard circuit simulator, so a dedicated software is not essential. SPICE can be used as a tool to solve Maxwell's equations based on a network analogue, like the lumped-element network that consists of inductance, resistance and capacitance components.

To find the solution of the lumped-element network, SPICE assumes a linear system and finds the solution using standard methods [8]. An alternative to the lumped-element network is the transmission line equivalent and can be also used as a network analogue to solve Maxwell's equations. SPICE can be applied to solving this kind of problem. There is a number of either commercial or free versions of this programme. A number of circuit simulators can be found, but a review of the state-of-the-art is beyond the scope of this work. Some examples of circuit simulators based on Berkeley's code are: NGSPICE, TOPSPICE, WRSPICE, and other non-based SPICE simulators are: APLAC (general purpose nonlinear circuit, system, and electromagnetic FDTD simulation and design programme) and the Applied Research Wave linear circuit simulator.

3. Method

The SpiceOpus light circuit simulator (V.2.2 Ljubljana University, Slovenia [19]) was used to simulate the loss return spectra of RLC series circuits, which were used as equivalent circuits for circular-shaped coils. Equivalent circuits of PERES coil with 4, 8 and 12 petals were also used to simulate coil performance via the loss return coefficients. Figure 1

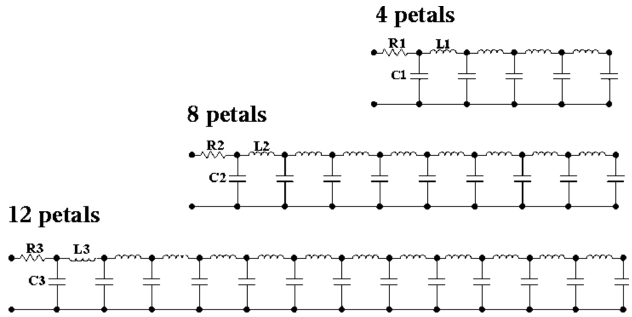

FIGURE 1. Three equivalent circuits of PERES coil for 4, 8 and 12 petal coils.

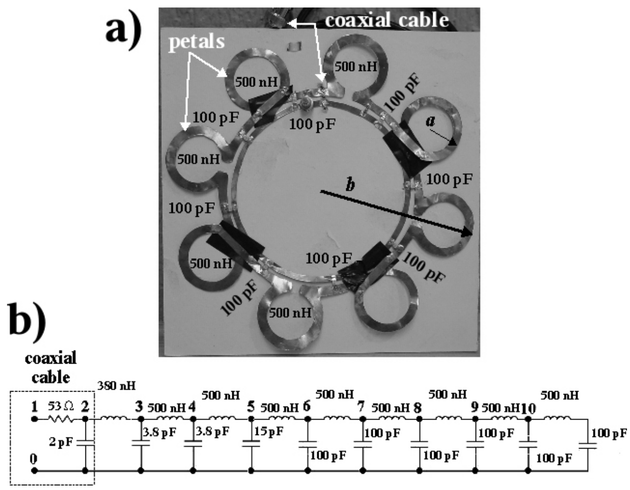

FIGURE 2. a) Diagram of PERES coil design with 8 petal coils with a = 1 cm radius and b =10 cm, b) equivalent circuit: L (500 nH) and C1 (100 pF) in the coil diagram are the inductance and the capacitance, respectively. The capacitance and inductance between nodes 1 and 2 represent the coaxial cable. Matching (L) and capacitance-balancing capacitors are between nodes 3 and 6, and tuning capacitors (C1) are from nodes 6 to 10. The inductance value between nodes 2 and 3 is represents (multi-turn coil) choke coil for 50 Ω matching purposes.

shows schematic diagrams of PERES coils for these three cases. The inductance value of the petal coils was numerically calculated using a dedicated-programme developed by Rodriguez and collaborators [20], because most inductance formulae do not consider circular-shaped coils formed with strip. To compare the simulated and experimental-acquired return loss of an RLC equivalent circuit, two coils were built with the following characteristics: a) a PERES coil prototype with a total radius of 10 cm and a 1 cm strip, 8 petal coils with 2 cm radius and a 0.3 cm strip, and b) a circular-shaped coil with a total radius of 10 cm. All coil prototypes were made out of copper with a 1 cm strip. Figure 2 shows a photo of the 8 petal-PERES coil design and its equivalent circuit with the corresponding values of capacitance and inductance.

These coil prototypes were connected to a network analyzer (Model R3753AH, Advantest Co, Tokyo, Japan) via a 50 Ω quarter-wavelength coaxial cable to obtain their return loss coefficients. Coil designs were tuned to 64 MHz and matched to 50 Ω. This frequency corresponds to the resonant frequency of hydrogen atoms subjected to a magnetic field intensity of 1.5 T. The quality factor for different circuit parameters was measured from the reflection coefficients of both simulated and experimental spectra, dividing the resonant frequency by 3 dB bandwidth as reported in Ref. 15.

4. Results and Discussion

Coil tuning and matching of the coil prototype was done and a diagram of the entire spectrum and its Smith chart are shown in Fig. 3. These two parameters ensure that the coil prototype is able to operate at the desired resonant frequency of 64 MHz and that, the energy transfer will be maximal, as indicated in the Smith chart. The tuning and matching measurements of the circular-shaped coil were calculated according to the method in Ref. 20. Figure 4 shows a comparison of loss return coefficient plots between a circular-shaped coil prototype and its corresponding simulated spectrum. Coaxial cable electrical characteristics were included in the equivalent circuit as depicted in Fig. 2 for a more realistic simulation. A good agreement can be observed between the experimental and simulated spectra for a simple coil configuration. The simulated spectrum shows a better attenuation capacity; however, the difference in attenuation can be explained by the coil construction imperfections.

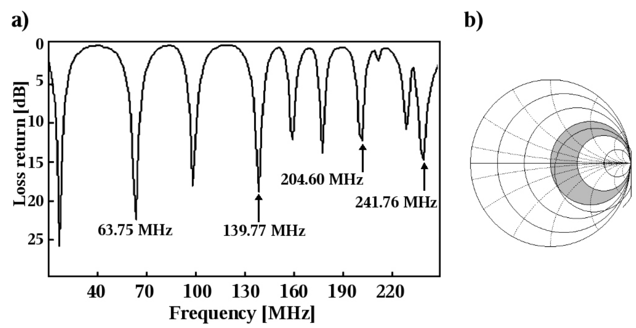

FIGURE 3. Tuning and matching of the coil prototype: a) entire spectrum [5 Hz - 250 MHz] showing the resonant frequency, 64 MHz and the harmonics, and b) 50 Ω matching to assure maximum energy transfer to the MR imager.

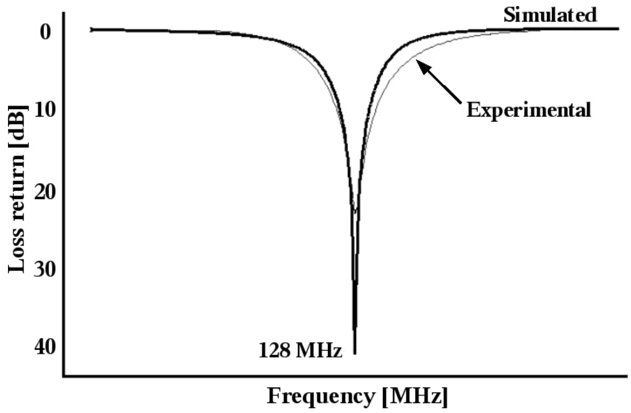

FIGURE 4. Comparison of simulated and experimental spectra of return loss coefficients at 64 MHz (1.5 T) for a circular-shaped coil.

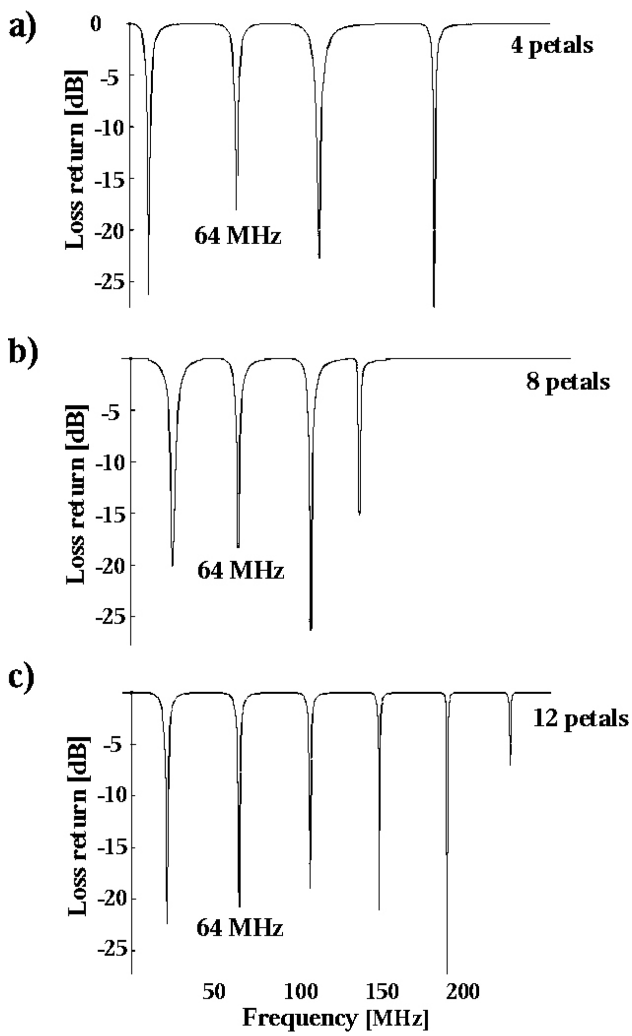

FIGURE 5. Loss return coefficient spectra of three equivalent circuits for different PERES coil configurations. A resonant frequency of 64 MHz was assumed.

TABLE I. Electrical characteristics of various PERES coil configurations.

Number of petals	Frequency [MHz]	Quality factor (Q)	Attenuation [dB]
4	63.91 ± 3.39	1282	20.07 ± 2
8	64.25 ± 3.02	1205	27.20 ± 2.7
12	63.85 ± 3.38	1894	27.62 ± 2.7

TABLE II. Comparison of harmonics between the experimental and simulation loss return coefficients.

Resonant mode	Frequency [MHz] (Experimental)	Frequency [MHz] (Simulation)	% Error
1	63.75	63.97	0.003
2	139.77	140.8	0.007
3	200.1	198.43	0.008
4	228.2	230.4	0.009

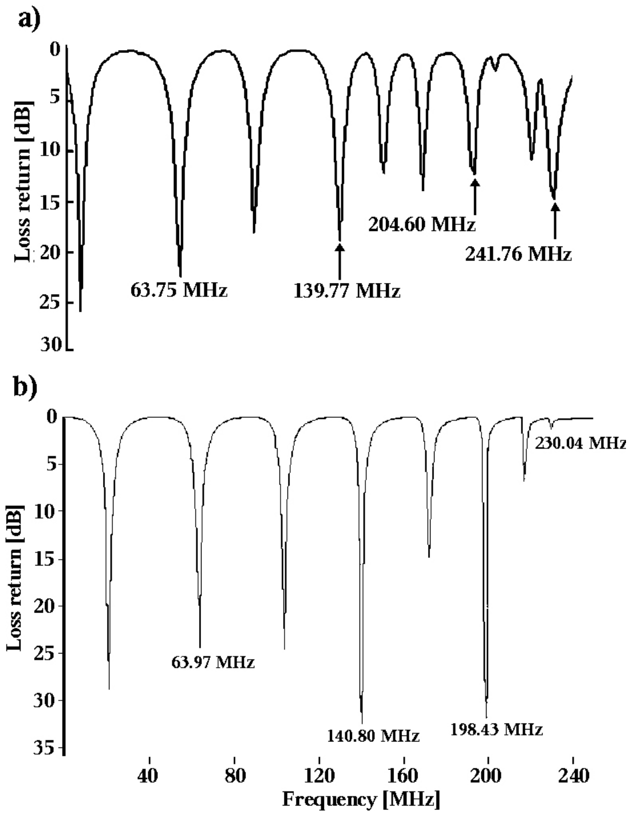

FIGURE 6. Whole spectra of 8 petal PERES coil using: a) simulation of the equivalent circuit, and b) experimental prototype coil.

The coaxial cable can be an important source of noise mainly when it is not properly attached to the coil prototype, and this effect can be observed in a loss return coefficient plot. Coaxial cable was included in the equivalent circuit and simulated together with the coil to identify possible sources of spurious effects originating in the coil. To avoid unwanted spurious signals from the coaxial cable, it is necessary to look carefully at its electrical specifications and to make sure that the cable is properly attached to the copper strip. In this case, the coaxial cable contributions did not cause evident extra peaks in the spectrum.

Simulated spectra of the PERES coil were obtained for different configurations and showed a very similar pattern. Figure 5 shows spectra for various PERES coil layouts; the resonant frequency and their harmonics can be effortlessly identified prior to building a coil prototype for all cases, saving a significant amount of time and effort. There is a small increment in the number of peaks from 8 petal to 12 petal configuration. Simulation of the loss return coefficients is able to show all the harmonics of the PERES coil. Figure 6 shows comparison plots of the loss return coefficients of both coil designs. These plots can be particularly helpful in identifying those spurious effects caused by imperfections construction, mutual inductance, quality of coaxial cable, etc. Spurious effects usually appear in the spectrum as peaks on either side of the resonant frequency or other harmonic peaks, because small circuits are formed with different artificial frequencies.

To experimentally investigate the behaviour of the coil performance, the quality factor, attenuation, and the resonant frequency were computed for all cases. The electrical characteristics are summarised in Table I. It can be observed that the number of petals do not affect coil performance. There is no strong evidence indicating that coil performance and penetration capacity is affected by the number of petals. When using too many petal coils, it is important to consider that the distance between coil centres should be at least $3a$ to avoid mutual inductance, since this effect can degrade the coil performance [15-17]. This is simply because it is necessary to accommodate more petal coils in the same coil and the minimum coil centre distance decreases.

From the 8 petal PERES coil design, a loss return coefficient plot was computed to evaluate the coil performance and compare the coil harmonics against those obtained via the simulation approach. Fig. 7 shows the simulated spectra of an equivalent circuit of 8-petal PERES coil and the experimentally-acquired spectra of a coil prototype with the same dimensions and parameters. Spectra show a relatively good agreement between experimental and simulated loss return coefficients. Penetration capacity is practically the same. While the resonant frequency is the same for all cases, the harmonics are shifted by a small frequency value. It is important to mention that perfect capacitors were assumed to perform this simulation, so a difference is expected since no perfect chip capacitors can be manufactured. Tuning and matching ceramic capacitors used in all coil designs have a 10% uncertainty. To fine-tune a coil, trimmer capacitors are normally used to add that small capacitance to improve the resonant frequency figure. Trimmer capacitors were not included in this simulation to simplify calculations, because the

TABLE III. Comparison of electrical parameters of the coil prototype and the equivalent circuit simulation.

	Resonant frequency [MHz]	Impedance [Ω]	Quality factor	Attenuation [dB]
Equivalent circuit simulation	63.84 ± 3.3	54 ± 5.40	613.26	32.00 ± 3.2
PERES coil prototype	63.90 ± 3.4	57.24 ± 5.72 (57.22 j - 1.72)	661.34	27.64 ± 2.7

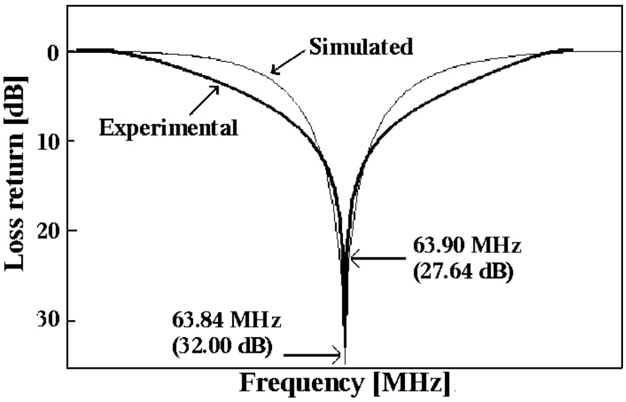

FIGURE 7. Comparison of simulated and experimental spectra at 64 MHz (1.5 T). The PERES coil as shown in Fig. 3 was used and its return loss coefficients were computed.

contribution is usually small compared with the total capacitance in the coil.

Table II summarises the resonant mode values of PERES coil for both the experimental and simulated spectra and their corresponding percentage error. From Fig. 7, quality factors were calculated and summarised in Table III. There is good agreement between simulation-acquired quality factors and experimental factors according to the data in Tables I and III. This implies that using an equivalent circuit of an RF coil to simulate its performance is a reliable method, despite the fact that is based on a linear-equation system. The impedance difference of around 4Ω did not affect the quality factor of the PERES coil. As a rule, it is very unlikely in practice to obtain an impedance value lower than 54Ω. However, the attenuation is affected by an 8.84 dB reduction with respect to the simulation result. This can be explained by the construction imperfections, mainly due to the assembling of the coaxial cable to the coil prototype.

Mutual interaction can also be included in this type of simulation, particularly for the study of the interaction of petal coils when the separation of the coil centres is less than 2 a. Other types of RF coils with complex configurations can also be studied with the aid of an equivalent RLC circuit simulation, before any attempt to build a coil prototype is made. The SpiceOpus light circuit simulator only offers a first approximation to the solution because it is based on a linear equation system. However, the information is still relevant for the development of complex coil geometries of PERES coil designs. This is mainly due to the fact that a) the main resonant mode and spurious peaks can be easily identified, b) performance (quality factor) can be assessed previously to build a coil prototype, and c) different configurations of petal coils (square, rectangular, and elliptical) can also be studied. A further investigation to study coil performance with equivalent-circuit simulate coil may include a transmission-network analogue.

5. Conclusion

It has been demonstrated that it is possible to simulate the spectra of return loss coefficients of PERES coils via an equivalent circuit. These idealised equivalent circuits can only offer approximate solutions to the coil performance under test. It has been proved that the simulation of PERES coil performance via an equivalent circuit is a good alternative to the trail-and-error approach widely used to develop dedicated coils for MRI applications.

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