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Spherical and Improved Helmholtz Coil with High B_1 Homogeneity for Magnetic Resonance Imaging

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Abstract: Several types of volume RF coils such as Helmholtz pair have been used for Magnetic Resonance Imaging. However, the field uniformity of a coil has always been suffering from a critical issue in imaging accuracy. The presented work is a study and design of spherical and improved radiofrequency Helmholtz coil which produces a high B_1 magnetic field homogeneity. This coil is composed of four coaxial rings of wire, which are symmetrically located on a spherical surface. Each two rings on the same side have the same tuning capacitor. In contrast with the standard Helmholtz pair, which is of 2nd-order magnetic field homogeneity, the proposed coil provides fourth-order magnetic field homogeneity. The developed spherical structure is tested experimentally in free space and compared with results obtained with equivalent standard Helmholtz coil. The results lead to conclude that the proposed structure provides better B_1 Homogeneity than the Standard Helmholtz type coil. Thus, the relative width at 1% of the profile is 1.37 times greater for the spherical Helmholtz coil. Similarly, the spherical Helmholtz coil has shown to have an increased efficiency and quality factor is of great interest.

Keywords: RF Coils, Magnetic Field Measurement, Magnetic Flux, Helmholtz Coil Design, Inductive Coupling, MRI

Introduction

Volume RF coils (Hayes *et al*., 1985; Syms *et al*., 2005) are designed to produce a homogeneous RF excitation across a massive volume. Most clinical MRI scanners embed an inbuilt volume coil to perform full-body imaging and smaller volume coils have been constructed for the head and other extremities.

Common designs for volume coils include Birdcage Coils and Saddle Coils. These coils require a huge amount of RF power because of their size, therefore they are often driven in quadrature (Anderson, 1999; Bongiraud *et al*., 1999; Michael, 1991; Mispelter *et al*., 2006; Hu *et al*., 2012; Azpurua, 2012).

It is very important that the coil generates a very uniform B_1 magnetic field because a coil which generates an inhomogeneous field will have an inhomogeneous sensitivity and any in-homogeneities will introduce distortions into obtained images.

Helmholtz coils or Helmholtz pair coils (Villa *et al*., 1999), which produces a 2nd order B_1 field homogeneity, is a volume coil and constitutes of two circular rings parallel to each other and kept apart by a distance equal to the radius of rings. They are utilized as the z gradient coils in MRI scanners facilitating localization in the z direction (head to foot in a horizontal magnet). They may also be used occasionally as RF coils for pelvis imaging and cervical spine imaging.

In the present research study, the analysis and design of a spherical radiofrequency coil, derived from the Helmholtz coil, is developed and demonstrated. The developed structure is comprised of four co-axial coils of wires erected symmetrically on a spherical surface. The main objective is to produce better performances with respect to B_1 homogeneity in contrast with the Helmholtz coil. Thus, the proposed probe provides a fourth order B_1 field homogeneity. At electrical level, the probe is constituted two circuits, each one comprises two coils mounted in series and tuned by a common capacitor. Thus, the proposed probe has two resonant modes as Helmholtz pair.

An accurate electrical model will permit to get all parameters for the co-current mode which is the homogenous mode.

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Quantification of B_1 field in free space permits to compare the probe performances with that of the obtained by standard Helmholtz pair.

B_1 Field Homogeneity

In the direction of the axis of a single circular loop of wire drawing a current I, if the origin of the coordinates is taken at the middle of the loop and the z axis is taken along the coil axis, the magnitude of the magnetic field B, which points in the *z* direction, holds the Biot-Savart Law (Feynman *et al*., 1963):

$$B_{1y} = \frac{\mu I}{2a\left(1+\left[z/a\right]^2\right)^{3/2}} \quad (1)$$

Here, z is the distance from the origin (O) and $\mu = 4\prod 10^{-7}$ H/m is called the permeability of free space. In Cartesian coordinates, the optimization of B_1 homogeneity produced by a structure comprises two identical coaxial loops carrying the same current is identical to the study of the field homogeneity produced by the Helmholtz coil pairs, where the loops are placed symmetrically along a common axis, one on each side of the experimental area and separated by a distance equal to the radius of the coil.

The developed structure of the coil comprises four coaxial rings and assembled symmetrically on a spherical surface. The Geometry of the spherical Helmholtz structure is given in Fig. 1.

On this basis, It can be calculated the total magnetic field B_1 due to the proposed structure which is comprising four loops of radius r_i carrying a steady currents I_i, at a point P along the axis of symmetry (where z_i is the distance between P the origin O:

$$B_{1z} = \sum_{i=1}^{4} \frac{\mu I_i}{2a_i} \frac{1}{\left(1+\left[\frac{z-z_i}{a_i}\right]\right)^{3/2}} \quad (2)$$

To study the field homogeneity produced by the proposed structure, we can use, the expression proposed by (Remeo and Hoult, 1984) to get the magnetic field axial component:

$$B_{1z} = \frac{\mu I}{2b} 1.95\left\{11.08\left(z/b\right)^6 - 0.023\left(z/b\right)^8 + \ldots\right\} \quad (3)$$

Generally, it can be possible to demonstrate using appropriate numerical calculations that this equation has several solutions for the proposed spherical structure (Mariappan and He, 2013; Vaughan and Griffiths, 2012).

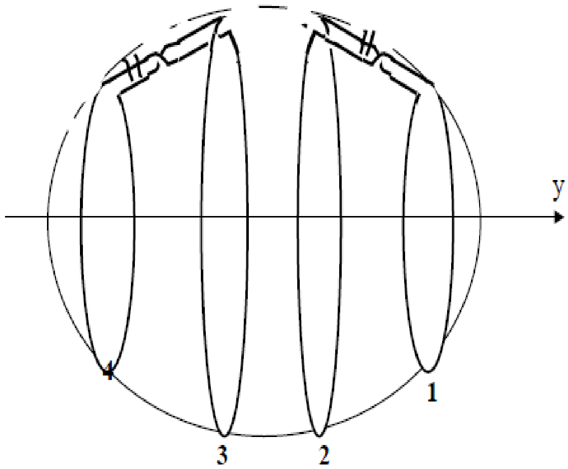

Fig. 1. Geometry of the spherical Helmholtz structure

Electrical Modeling

The proposed structure corresponds electrically to the study of the four-coil system. Thus, a complete electrical modeling should be useful in order to show and prove the operation and feasibility of the developed coil.

The self-inductance of a circular conductive loop made up of a circular wire can be determined using the approximate high frequency inductance (Feynman and Sands, 1996):

$$L_i \approx a_i \mu \left\{\ln\left(8\frac{a_i}{b_i}\right) - 2\right\} L_i \approx a_i \mu \left\{\ln\left(8\frac{a_i}{b_i}\right) - 2\right\} \quad (4)$$

where, μ_0 is the same as above, r_i is the radius of the loop *i* and *a* is the radius of the wire.

The mutual inductance, *M*, between two inductors circuits *i* and *j*, is a measure of the coupling between these two circuits. The expression of the mutual inductance is calculated by the double integral Neumann formula (Feynman and Sands, 1996) as illustrated in Equation 5:

$$M_{ij} = \frac{\mu_o}{4\pi} \oint \left[\oint \frac{ds_i}{d_{ij}}\right] ds_j \quad (5)$$

Here, μ_0 is the same as above, ds_i and ds_j are the curves occupied by the wires and d_{ij} is a distance between circuits.

The mutual inductance can be also expressed with the coefficient of coupling k_{ij}. The coefficient of coupling is always between 1 and 0 and is a convenient way to determine the relationship between a certain orientations of inductor with arbitrary inductance Equation 6 (Kim, 2011):

$$K_{ij} = M_{ij}\left(L_i L_j\right)^{-1/2} \tag{6}$$

M_{ij} is the mutual inductance between loop i and loop j. L_i is self-inductance for loop i, whereas $0< K_{ij} < 1$.

It should be noted that the tuning of the coils of proposed structure is done as simply as for Helmholtz coil pairs.

Figure 2 illustrates the loss free equivalent circuit of the four-coil configuration.

The developed coil is comprised of four circular loops tuned at the same frequency and magnetically coupled. It can be easily shown that two resonant modes are observed, one counter-current mode which is the gradient mode and one co-current mode, which is the homogenous mode that can be important for MRI. The value of tuning capacitor can be given by the homogenous mode.

Applying mesh analysis rule to the system, we can get the appropriate mesh system equations as shown in Equation 7:

$$\begin{cases} \left(j\frac{L_1}{L_2}\left(L_2\omega - \frac{1}{C_2\omega}\right) + j\,M_{14}\omega \right) I_1 + \left(j\left(M_{12}+M_{13}\right)\omega \right) I_2 = 0 \\ \left(j\left(L_2\omega - \frac{1}{C_2\omega}\right) + j\,M_{23}\omega \right) I_2 + \left(j\left(M_{12}+M_{13}\right)\omega \right) I_1 = 0 \end{cases}$$

$$Z_1 = jL_1\omega + jL_2\omega + \frac{1}{jC_1\omega} + 2jM_{12}\omega \tag{7}$$

$$Z_2 = jL_3\omega + jL_4\omega + \frac{1}{jC_2\omega} + 2jM_{34}\omega$$

From the above system equations, the resonance equation of the developed model coil can be expressed in Equation 8:

$$\begin{gathered} ZI_1 + j\left(M_{14}+M_{23}+2M_{13}\right)\omega I_2 = 0 \\ \left(L_1 + L_2 + 2M_{12} + M_{14} + M_{23} + 2M_{13} - \frac{1}{C}\right)\omega^2 = 0 \end{gathered} \tag{8}$$

If we use the coefficient coupling coefficients, the new resonance equation is Equation 9:

$$C\left(L_1 + L_2 + 2k_{12}\sqrt{L_1L_2} + 2k_{13}\sqrt{L_1L_2} + k_{14}L_1 + +k_{23}L_2\right)\omega^2 = 1 \tag{9}$$

This equation is of second order and has two solution, the positive reel solution which corresponds to the co-current mode, which is given in Equation 10:

$$f_1 = \frac{1}{2\pi\sqrt{\begin{gathered}C(L_1 + L_2 + 2k_{12}\sqrt{L_1L_2} + \\ +2k_{13}\sqrt{L_1L_2} + k_{14}L_1 + k_{23}L_2)\end{gathered}}} \tag{10}$$

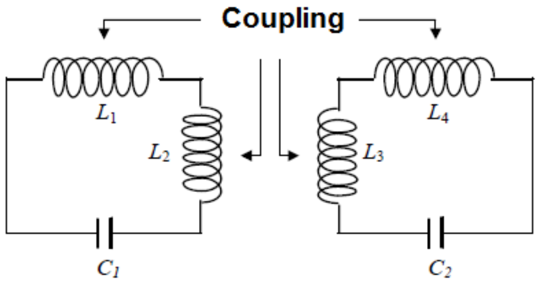

Fig. 2. Lossless equivalent circuit of the four-coil configuration

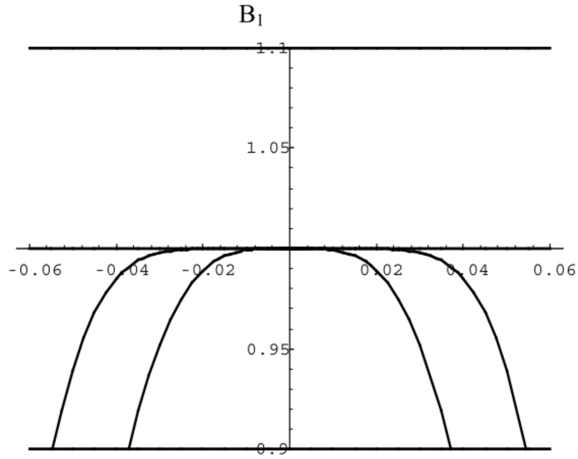

Fig. 3. Normalized axial profiles of B_1 parallel to the coil axis

Simulation Results

After numerical calculations, it becomes clear to show that the proposed spherical structure (S) produces a certain range of possibilities with undulations and one geometric configuration which produces a fourth-order homogeneous field Fig. 3.

For the proposed spherical structure and Helmholtz type pairs which is contained in the same sphere used as a reference, the axial magnetic field is computed with the help of the Biot–Savart Law (see Equation (Hayes *et al*., 1985)) and normalized to its value at origin (Ghaly and Al-Sowayan, 2014b).

As per as the B_1 homogeneity is concerned, Fig. 3 clearly illustrates the increase of the axial profile widths for the proposed spherical structure in contrast with the Helmholltz type pairs. In fact, the axial profile width at 10% is approximately 1.50 times greater for the developed spherical coil and the axial profile width at 1% is approximately 1.20 times larger for our proposed spherical structure/model.

Results and Discussion

In this chapter, experimental outcomes using a network analyzer HP4195A are presented. Thus, measurements of the axial B_1 field were brought out for developed coils along their axis and in free space without load.

Fig. 4. Photograph of the Helmholtz coil

Fig. 5. Photograph of the spherical prototype coil

Table 1. The exact dimensions of the coils

Coils	Diameter (cm) Middle loops	Diameter (cm) Outer loops	Distance (cm) Middle loops	Distance (cm) Outer loops
Helmholtz H	4.80	---	2.40	---
Improved Helmholtz S	4.80	3.42	1.21	3.60

Two prototypes coils were built for MRI (1H) at a frequency of 100,241MHz. A spherical prototype coil and a Helmholtz coil (H) which has the same radial size (4.8 cm) are used for results comparison, the accurate dimensions of these coils are shown in Table 1.

Figure 4 and 5 illustrate physical appearance of both coils (our prototype spherical coil S and Helmholtz coil H).

Calibration and Frequency Matching

Proper tuning and matching are essential in obtaining high optimal energy transfer. The coils must be well tuned and matched their impedances to the impedance of the transmission line to fulfill the maximum power transfer theorem. Thus, the four loops of the spherical coil are tuned to the same frequency f_0. Hence, the whole coil resonance frequency is adjusted by equally tuning each loop.

The developed coils are properly matched to the impedance of 50 Ohms by means of varying the inductive coupling in order to decrease reflected power and increases the quality factor Q. The important feature of this matching type is that the tuning and matching could be independently done (Ghaly *et al*., 2006; Ghaly and Al-Sowayan, 2014b; Ghaly *et al*., 2016).

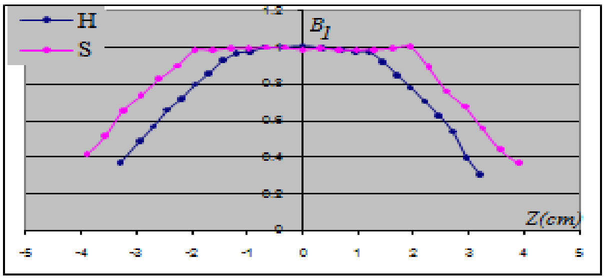

Fig. 6. Experimental profiles of the B_1 axial field for both coils

Table 2. Results obtained in free space without load

Coils	H	S
Lobe at 10%	2,89cm	3,83cm
Lobe at 1%	1	1.32
Efficiency	1	1.37
Quality factor	215	284

Measurements of the axial B_1 field in free space were conducted for the spherical structure S and the Helmholtz type pairs H. These measurements were carried out with the help of a small pick-up coil connected to the network analyzer (voltage measurement Transmit/Receive).

This technique allows to collect the B_1 field along the probes axis (OZ).

The magnetic field produced by the spherical coil and Helmholtz coil (H, S) are illustrated in Fig. 6.

The axial profiles of the B_1 field for the two coils (Fig. 6) are good agreement with theoretical and simulations predictions (Fig. 4).

Table 2 shows the essential results obtained in free space without load for our coil compared to standard Helmholtz coil H (reference coil).

Conclusion

First, this research work states to be a contribution in the general context of magnetic field homogeneity. In fact, the magnetic field homogeneity produced by a standard Helmholtz-type can be improved by the addition of extra coaxial rings.

Secondly, an improved Helmholtz-type coil that can be used for MRI is built. It constitutes of four circular coaxial rings of wire in a symmetric arrangement on a spherical surface (S).

Further, a standard Helmholtz-type Pairs is also built for comparison. The two developed coils have in fact two symmetrical tuned elements that consist of two different lateral coils mounted in series with a tuning capacitor.

It is shown that B_1 homogeneity produced by the improved Helmholtz coil is fourth order and second order for standard Helmholtz coil.

An electrical modeling taking into account the couplings among all rings that defines the operating conditions of co-current mode is presented.

Measurements of B_1 field were done in free space to check the B_1 homogeneity by finding their axial profiles. Thus, compared to the standard Helmholtz-type, the relative width at 1% of the profile is 1.37 times larger for the improved Helmholtz S. Similarly, an improvement of the quality factor and efficiency are observed for the improved Helmholtz S compared to the standard Helmholtz-type.

At the outset, the proposed scheme can also be implemented to the cases of Helmholtz-types having different topologies with respect to geometry and structures, a simple cylindrical geometry can be a case to be enhanced.

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Author's Contributions

Sidi M. Ahmed Ghaly: Participated in the general idea of construction of a typical Helmontz and Spherical coil, coordinated the data-analysis, carried out simulations and demonstrated all experiments and documented the results, Organized the study and research plan.

Khalid A. Al-Snaie: Participated in the experimental results using a network analyzer HP4195A for measurements of the axial B_1 field using modified coils along their axis and in free space without load. Also coordinated in the data-analysis and manuscript review and draft.

Obaidullah Khan Mohammad: Participated in the core idea of the research by literature survey of high B1 Homogeneity for MRI, participated in the experimental setup and design also noted the simulation outcomes for different topological coil systems, coordinated the data-analysis and contributed to the writing of manuscript by editing and revising and addressing the article as per the comments and directions of the reviewers.

Ethics

The authors declare that the present article is a novel work and an outcome of original and exhaustive literature survey in the field and the maximum possible references are given under.

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