Modern Applied Science; Vol. 10, No. 5; 2016
ISSN 1913-1844 E-ISSN 1913-1852
Published by Canadian Center of Science and Education

Design and Testing of Radiofrequency Spherical four Coils

Sidi M. Ahmed Ghaly[1], Khalid. A. Al-Snaie[1] & Sulaiman S. Al-Sowayan[1]

[1] Department of EE, College of Engineering, Al Imam Muhammad Ibn Saud Islamic University (IMSIU), Riyadh, Saudi Arabia

Correspondence: Sidi M. Ahmed Ghaly, Department of EE, College of Engineering, Al Imam University, Riyadh, Saudi Arabia. Tel: 966-11-25-86519. E-mail: smghaly@imamu.edu.sa

Received: March 20, 2015 Accepted: March 31, 2015 Online Published: April 2, 2016

doi:10.5539/mas.v10n5p186 URL: http://dx.doi.org/10.5539/mas.v10n5p186

The research is financed by the deanship of Academic research at Al Imam Mohammad Ibn Saud Islamic University.

Abstract

In this paper, we present the design and testing of a radiofrequency prototype coil with good performances in terms of B_1 magnetic field homogeneity and can be utilized for Magnetic Resonance Imaging. It is constituted of four coaxial separately tuned rings of wire and symmetrically located on a spherical surface. Compared to standard Helmholtz pair, which has 2nd-order magnetic field homogeneity, it yields to improvement in field homogeneity, while preserving the simplicity of design. The four coils of proposed structure are tuned to the same frequency. The proposed structure gets at 4th-order magnetic field homogeneity by optimizing the distance between rings and the diameters of outer loops. An electrical modeling of the four-coil system taking into account the coupling effects between all rings permits to determine the resonance frequency in the homogenous mode. Measurements of B1 field homogeneity were introduced in free space. Compared to the Helmholtz coil, the proposed structure presents good performances in terms of B1 homogeneity, quality factor and sensitivity. The design of proposed coil has been optimized for best SNR performances. Globally, this work claims to be a contribution to the study of the four-coil RF systems derived from the Helmholtz pairs.

Keywords: B_1 homogeneity, magnetic field, helmholtz coil, mutual coupling, RF coil, MRI

1. Introduction

Radio frequency (RF) coil system (Hayes & Eash, 1985), (Syms & Gilderdale, 2005) is a critical component in a MRI system, which is an electrical device generally composed of multiple wire loops that can either generate a magnetic field or detect a changing magnetic field as an electric current induced in the wire.

A transmit and receive coil can send or transmit a B1 field and receive RF energy from imaged sample. After providing a transmitting excitation RF pulse as, the current source within a RF coil induces a B1 field inside the subject, which is called transmitting. The induced current in an RF coil is generated by the magnetization (M) in the imaged object, and this phenomenon is called receiving.

Much works have shown that the quality of the image obtained by MRI is, in particular, depending on the intensity of the homogeneity of radiofrequency fields (RF) B1T produced by the transmit coil and B1R associated with the receiving coil (Anderson, 1999), (Bongiraud & Jeandey, 1999), (Harpen, 1991), (Mispelter & ANMR, 2006),

In general, the homogeneity of the B1 field produced by the RF coils is in multiple radiating elements and their design is constantly optimized. Thus, for example Helmholtz coils (Villa & Ruiz-Cabello, 1999), which is the most popular in MRI and have good performance in terms of field homogeneity and signal-to-noise ratio (SNR). The optimization and electrical modeling of RF coils structures with periodic geometry are the subject of constant research. In this work, we take into account the problems of inductive coupling between all elements (rings) so that to facilitate the design process due to the periodic geometry of structure.

This article presents a study, design and testing of an Rf coil with spherical geometry and comprising four free elements (tuned rings).

Compared to Helmholtz coil, very interesting properties in terms of B_1 homogeneity and sensitivity are obtained.

Generally, this work concerned the aspects linked to the electronic instrumentation and, in particular, the design, modeling, optimization of RF coils for Magnetic Resonance Imaging, introducing a certain simplicity of implementation and having interesting performance in B1 homogeneity and the simplicity of design. In addition, different couplings and original matching are investigated.

Overall, this work, which includes both the theoretical aspects and experimental claims to be a contribution to the study and understanding of RF systems derived from Helmholtz coils.

B_1 Field Homogeneity

The magnetic field along the axis of a single circular loop of wire carrying a current I can be determined with the Biot-Savart law (Feynman & Sands, 1964).

$$B_{1\,y} = \frac{\mu_0 I}{2a(1+[y/a]^2)^{3/2}} \tag{1}$$

This expression provides the magnitude of the magnetic field of a single circular ring of wire of radius a carrying a current I as a function of distance y from the center of the coil to a point P on the central axis of symmetry. The constant μ_0 is called the permeability of free space and is equal to 1.26x10-6 Tesla·meter/Ampere (T·m/A).

Eq 1 can now be used to determine the magnetic field of four coils system as shown in Figure 1. Each ring is separated from the origin by the distance yi and ai is the radius of loop i. The magnetic field along their axis of symmetry at a point P a distance x from the origin can be determined for each loop and the fields can be added together for the final result. If the currents in each loop are in the same direction(co-current mode), then the fields will complement each other to produce a strengthened magnetic field at each point. If the currents flow in opposite directions(counter-current mode), the fields will counteract to produce a lesser field strength.

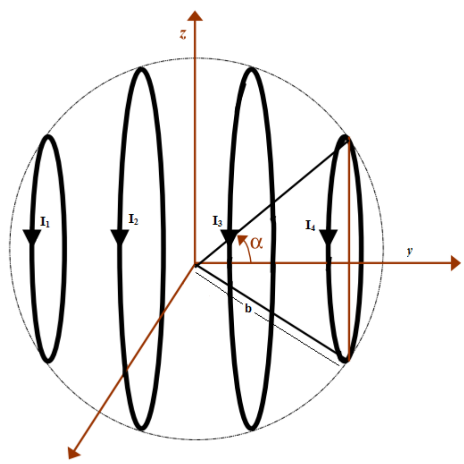

Figure 1. Geometry of the spherical four coils configurations

The total field $B_{1\,y}$ along the coil axis is given in Eq. 2.

$$B_{1\,y} = \sum_{i=1}^{4} \frac{\mu_0 I_i}{2\,a_i} \frac{1}{\left(1+\left[\frac{y-y_i}{a_i}\right]\right)^{3/2}} \tag{2}$$

Where y_i is the distance from the origin and a_i is the radius of loop i

We can expand the total magnetic field in a harmonic series of legendre polynomials using the formula proposed by Remeo and Hoult (Remeo & Hoult, 1984) and demonstrate that an homogenous field distribution can be obtained up to fourth order. Thus, the total magnetic field axial component is given in Eq. 3

$$B_{1\,y} = \sum_{i=1}^{4}(\mu_0 I_i/2\,r_i)\sin\alpha_i \quad \left\{\sum_{n=0}^{n=\infty} P_{n+1,1}(\cos\alpha_i)\ (y/r_i)^n\right\} \tag{3}$$

Where α_i angles are given in **Figure 1**, $P_{n,m}(\cos\alpha_i)$ are the associated Legendre polynomials, and $r_i = a_i/\sin\alpha_i$..

Using a numerical calculations, it can be showed that for the proposed spherical structure, the total magnetic field axial component is given in Eq. 4, which corresponds to a fourth order homogenous field.

$$B_{1x} = \frac{\mu I}{2b}\, 2.92\, \{1 - 1.10\,(x/b)^6 - 0.035\,(x/b)^8 + \ldots\} \tag{4}$$

The corresponding values of the proposed structures i. e. the spherical and Helmholtz coil are given in Table 1

Table 1. Dimensions of the coils

		Center loops	Outer loops	
	Radius	distance	Radius	distance
Helmholtz coil	2.4 cm	2.4 cm	--	--
spherical coil	2.4 cm	1 cm	1.75 cm	3.44 cm

2. Electrical Modeling

An electrical modeling of the proposed structure is useful to show its operation. The self-induction of circular loop of small size compared to the wavelength, can be expressed by the approximate high frequency inductance (Feynman & Sands, 1996) in eq. 5:

For circular loop i with radius a_i , the round copper wire radius is b_i

$$L_i \approx a_i \mu_{\circ} \left\{ \ln\left(8 \frac{a_i}{b_i}\right) - 2 \right\} \tag{5}$$

The mutual inductance by a filamentary circuit i on a filamentary circuit j is given by the double integral Neumann formula as shown in **Eq. 6**:

$$M_{ij} = \frac{\mu_{\circ}}{4\pi} \oint \left[\oint \frac{ds_i}{d_{ij}} \right] ds_j \tag{6}$$

Where μ_0 denotes the magnetic constant. is the permeability of free space, ds_i and ds_j are the curves spanned by the wires and d_{ij} is a distance between circuits.

The coupling between two coaxial circuits can be defined by **eq. 7**:

$$\boldsymbol{K_{ij} = M_{ij}\,(L_i\ L_j)^{-1/2}} \tag{7}$$

$\boldsymbol{M_{ij}}$ is mutual inductance between loop i and loop j

$\boldsymbol{L_i}$ is self-inductance for loop i and $0 < \boldsymbol{K_{ij}} < 1$

The self-inductances L_i, L_j do not depend on the distance whereas the mutual inductance does.

It should be noted that the four coils of spherical structure are individually tuned to the same frequency.

Figure 2 shows the lossless equivalent circuit of the four-coil configuration.

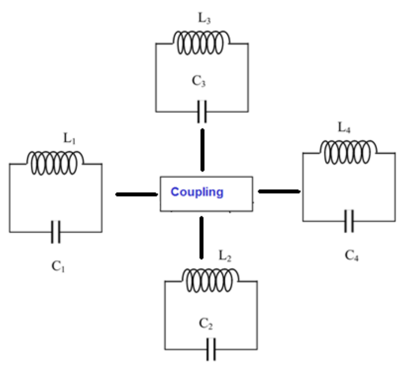

Figure 2. Lossy equivalent circuit of the four-coil configuration

The proposed structure is constituted of four circular coils, magnetically coupled and each resonating at the same frequency. Thus, four resonant modes will be obtained, three counter-current modes, corresponding to a gradient modes (upper frequency) and one co-current mode, corresponding to the homogenous mode (lower frequency), which is appropriate for MRI.

The homogenous mode allows getting the values of tuning capacitors.

Applying Kirchhoff's voltage low to the four circuits, the appropriate mesh equation can be expressed in **Eq 8** :

$$\begin{cases} \left(\mathrm{j}\frac{L_1}{L_2}\left(L_2\omega-\frac{1}{C_2\omega}\right)+\mathrm{j}\,M_{14}\omega\right)I_1+ \\ (\mathrm{j}\,(M_{12}+M_{13})\omega)I_2 = 0 \\ \left(\mathrm{j}\,\left(L_2\omega-\frac{1}{C_2\omega}\right)+\mathrm{j}\,M_{23}\omega\right)I_2+ \\ (\mathrm{j}\,(M_{12}+M_{13})\omega)I_1 = 0 \end{cases} \tag{8}$$

The resonance equation of the proposed structure can be also written in **Eq. 9**:

$$\begin{cases} L_1L_2-(2L_1L_2+L_1M_{23}+L_2M_{14})\frac{\omega^2}{{\omega_0}^2}+ \\ [(L_1+M_{14})(L_2+M_{23})-(M_{12}+M_{13})^2]\frac{\omega^4}{{\omega_0}^4}=0 \\ 1-(2+K_{14}+K_{23})\frac{\omega^2}{{\omega_0}^2}+ \\ [(1+K_{14})(1+K_{23})-(K_{12}+K_{13})^2]\frac{\omega^4}{{\omega_0}^4}=0 \end{cases} \tag{9}$$

This equation may be solved by a conventional method and the solution is given in **Eq. 10** for the co-current mode (homogenous mode).

$$\left(\frac{\omega_1}{\omega_0}\right)^2=\frac{2+K_{14}+K_{23}-\sqrt{(K_{14}-K_{23})^2+4(K_{12}+K_{13})^2}}{2[(1+K_{14})(1+K_{23})-(K_{12}+K_{13})^2]} \tag{10}$$

The current ratio between the center and outer loops of the proposed spherical structure can be expressed in Eq. 11

$$\left(\frac{I_1}{I_2}\right)_{\omega_1}=\sqrt{\frac{L_2}{L_1}}\cdot\frac{K_{14}-K_{23}-\sqrt{(K_{14}-K_{23})^2+4(K_{12}+K_{13})^2}}{2(K_{12}+K_{14})} \tag{11}$$

The corresponding values of the tuning capacitors and resonant frequencies are given in **Table 2**. These values are obtained from Eq. 9

Table 2. Corresponding values of the tuning capacitors and resonant frequencies

	Resonance Frequency (MHz)	Tuning capacitor (pF)
Helmholtz coil	105.17	19.49
spherical coil	118.53	C_1=C_4=21.23 C_2=C_3=16.41

3. Simulation Results

Figure 3 shows the axial profiles of the $\mathbf{B_1}$ field for proposed structures, our prototype spherical coil and Helmholtz coil which is contained in the same reference sphere. The field is calculated by using the Biot–Savart Law (see Eq. [1]) and normalized to its maximum value (Ghaly & Al-Sowayan, 2014).

Thus, for the spherical coil, there is a single and optimal solution with 4^{th} order homogeneity.

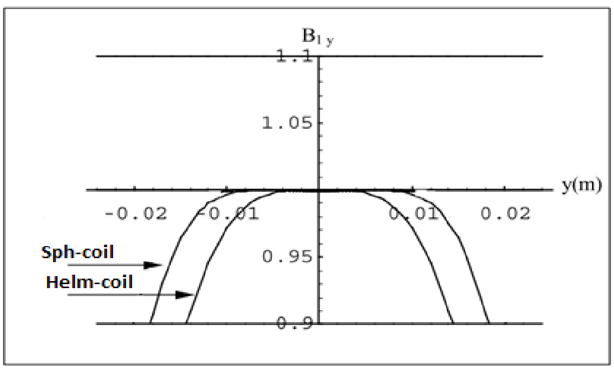

Figure 3. Normalized axial profiles of B1(y is along the coils axis)

Figure 3 shows clearly that the spherical structure has good performance in terms of the B1 homogeneity. Thus, compared to the Helmholtz coil, the relative width at 1% of axial profile is 1.56 times larger for the spherical structure and at 10% the axial profile of the spherical structure is 1.26 times larger than that of the Helmholtz coil.

It appears that cylindrical coordinates (Knoepfel, 2000) is the most appropriate coordinate system to find the magnetic field B1 in 3D at arbitrary point, due to a circular loop of wire carrying a current I and having a radius.

Applying to our four coils system, the total Magnetic field B1 produced by the four coils can be expressed by **Eq 12**, thus, we find the components are given by:

$$\begin{cases} B_\rho = \sum_{i=1}^{4} \frac{\mu_\circ I_i}{4\pi\rho} \frac{y-y_i}{\sqrt{(a_i+\rho)^2+(y-y_i)^2}} \\ \left[-K(k) + \frac{{a_i}^2+\rho^2+(y-y_i)^2}{(a_i-\rho)^2+(y-y_i)^2}\, E(k)\right] \\ \\ B_y = \sum_{i=1}^{4} \frac{\mu_\circ I_i}{4\pi\sqrt{(a_i+\rho)^2+(y-y_i)^2}} \\ \left[-K(k) + \frac{(y-y_i)^2-{a_i}^2-\rho^2}{(a_i-\rho)^2+(y-y_i)^2}\, E(k)\right] \end{cases} \tag{12}$$

Where y_i is the distance from the origin,

Where E(k) and K(k) are known as the complete elliptic integral of the first kind and the second kind

$$K(k) = \int_0^{\pi/2} \frac{d\alpha}{\sqrt{1-k^2 sin^2\alpha}} \;,\; E(k) = \int_0^{\pi/2} \sqrt{1-k^2 sin^2\alpha}\; d\alpha \;,\quad k = \sqrt{\frac{4a\rho}{(a+\rho)^2+x^2}} \tag{13}$$

Figure 4 shows the mapping plot of the magnetic field B_1 created by the spherical structure (y is along the coil axis)

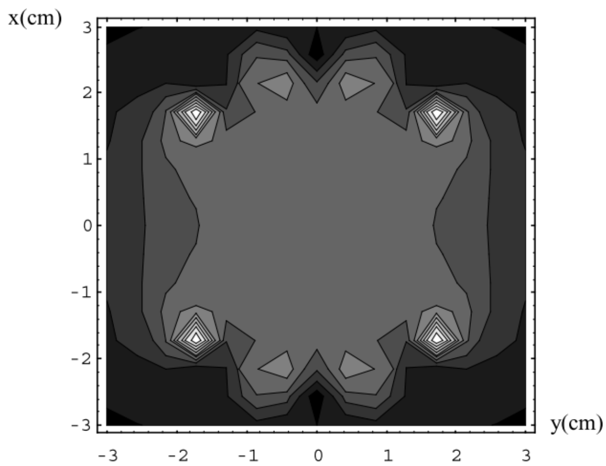

Figure 4. Mapping of the magnetic field created by the spherical structure

4. Experimental Results

In this section, we present the experimental results obtained with the proposed spherical coil and with the Helmholtz coil which is contained in the same reference sphere. Measurements of the B1 field were carried out in free space (test without load) using a network analyzer HP4195A, these tests have achieved relative profile of the B1 field along the coils axis.

Two coils were built; a spherical structure with four free elements (S) having an outer diameter equal to 4.80 cm, and a Helmholtz coil (H) of the same diameter (4.8 cm) as reference. Table. 3 gives the exact Dimensions of these coils:

Table 3. The exact dimensions of the coils

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

Figure 5 and Figure 6 show photographs of both coils (our prototype spherical coil S and Helmholtz coil H:

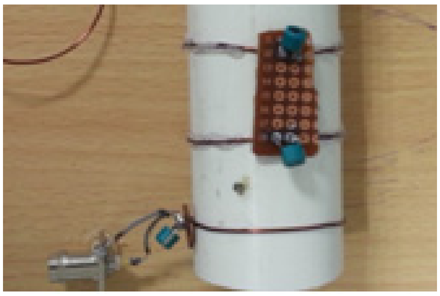

Figure 5. Photograph of the Helmholtz coil

Figure 6. Photograph of the spherical prototype coil

5. Tuning and Matching

For optimal energy transfer, the coils must be tuned and their impedances must be matched to the impedance of the transmission line. Thus, the four coils are tuned to the same frequency f_0. Hence, The resonance frequency of the whole coil is adjusted by equally tuning each circuit.

The impedance of the coils was matched to the impedance of 50 by using Inductive coupling because it reduces reflected power, increases the quality factor Q and its main advantage is that the tuning and matching could be made independent (Ghaly & Canet, 2006), (Guendouz & Canet, 2008).

Comparative tests in free space were carried out between the spherical coil S and the Helmholtz coil H. Thus, measurements of relative field along the axis of the coils were done by using a small pick-up coil connected to the network analyzer (voltage measurement Transmit / Receive).

This technique permits us to collect the magnetic field along the coil axis(Oy). Figure 7 shows the magnetic field produced by the both coils (H, S):

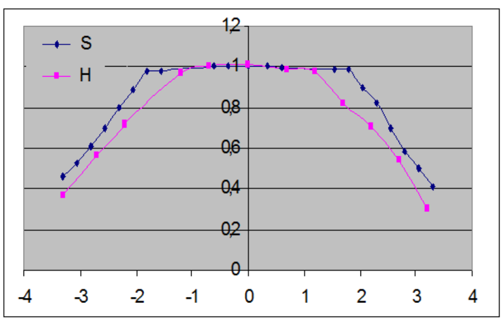

Figure 7. Experimental profiles of the B1 axial field for both coils

To compare the axial profiles, we determine the relative widths of the lobe at 10%. Thus, it is 1.43 times greater for the spherical coil, which is in accordance with theoretical predictions (see, Figure 3)

Similarly, for the same power consumption, it is possible to check the efficiency of coils (H, S). Thus, the field at the center is 1.35 times greater for the spherical coil S.

In addition, an improvement of quality factor is observed. It increased from 215 for the Helmholtz coil to 290 for the spherical coil (35%).

6. Discussion and Conclusion

The optimization of the RF coils performance, in particular the B1 homogeneity remains under constant research. In this work, the design and testing of spherical four coils is conducted. It is constituted of four circular coils magnetically coupled and in a symmetric configuration on a spherical surface.

For comparison, a Helmholtz coil was built and compared its performances with our prototype.

Using a numerical calculation of the appropriate field, in cylindrical coordinates and using Legendre polynomials, it was shown that B1 homogeneity is fourth order for the spherical structure.

An electrical modeling takes into account the couplings between all rings and defines the operating conditions of co-current mode is presented.

Measurements of B1 field were investigated in free space. These measurements verify the homogeneity of the B1 field by obtaining axial profiles. Thus, compared to the Helmholtz coils, the relative width at 10% of the profile is 1.45 times larger for the spherical structure. Similarly, an interest increasing of the quality factor and efficiency are observed for the spherical structure compared to the Helmholtz coil.

In terms of perspective, the proposed approach can be applied to the case of Helmholtz coils having other geometries, or to other structures, for example of simple cylindrical geometry.

Acknowledgments

The authors would like to thank the deanship of Academic research at Al Imam Mohammad Ibn Saud Islamic University for the financial support of the project: No 341402/1434H.

References

Anderson, T. (1999). *Design of a helmholtz coil for susceptibility testing using variational calculus and experimental verification.* IEEE International Symposium on Electromagnetic Compatibilitym, 601-604.

Bongiraud, J. P., Cauffet, G., & Jeandey, C. (1999). *An optimization method for magnetic field generator* (2nd). International Conference on Marine Electromagnetic, Francia.

Feynman, R. P, Leighton, R. B., & Sands, M. (1964). *The Feynman Lectures on Physics, 2*. Reading, MA Addison-Wesley.

Feynman, R.P., & Sands, M. (1996). The law of induction. In: Feynman, R. P., Leighton, R. B., & Sands, M. (Eds.), *The Feynman Lectures on Physics* (p17). Massachusetts : AddisonWeseley, 2.

Guendouz, L., Ould, S. M., Ghaly, A., Hedjiedj, A., Escanyé, J. M., & Canet, D. (February 2008). Improved Helmholtz-type magnetic resonance imaging coils with high-B1homogeneity Spherical and ellipsoidal four-coil systems. *Concept in Magnetic resonance,* 9–20.

Hayes, C. E., Edelstein, W. A., Schenck, J. F., Mueller, O. M., & Eash, M. (1985). An efficient, highly homogeneous radiofrequency coil for whole-body NMR imaging at 1.5 T. *Journal Magnetic Resonance,* 622–628).

Knoepfel, H. E. (2000). Magnetic Field: A comprehensive theoretical treatise for practical use. Hardcover.

Michael, D. H. (1991). The Spherical Birdcage Resonator, International. *Journal of Magnetic Resonance,* 550-556.

Mispelter, J., Lupu, M., & Briguet, A. (2006). Probeheads for Biophysical and Biomedical Experiments—Theoretical Principles and Practical Guidelines. London: Imperial College Press.

Ould, S. M., Ghaly, A., Guendouz, L., Hedjiedj, A., Escanye, J. M., & Canet, D. (2006). *Improved Helmholtz type coils with high-B1 homogeneity: spherical and ellipsoidal configurations,* 226–230. Innsbruck, Austria. Proceedings of the 24th IASTED International Conference on Biomedical Engineering.

Remeo, F., & Hoult, D. I. (1984). Magnet field profiling: analysis and correcting coil design. *Magnetic Resonance in Medicine,* 44-65.

Sidi, M., Ahmed, G., & Al-Sowayan, S. (2014). A high B1 homogeneity generation using free element elliptical four-coil system. *American Journal of Applied Sciences, 11*(4), 534-540.

Syms, R. R. A., Ahmad, M. M., Young, I. R., Li, Y., Hand, J., & Gilderdale, D. (2005). MEMS Helmholtz coils for magnetic resonance imaging. *J. Micromech. Microeng,* 1307-1317.

Villa, P., Vaquero, J. J., Chesnick, S., & Ruiz-Cabello, J. (1999). Probe efficiency improvement with remote and transmission line tuning and matching, Magnetic. Resonance. Imaging,