MAGNETIC FIELD SIMULATION OF GOLAY AND MAXWELL COILS

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To the late Associate Professor Dr Rashdi Shah Ahmad.

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ABSTRACT

Magnetic field gradient coils are essential in obtaining accurate magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) signals by generating magnetic field gradient in each x, y and z direction. Two of the parameters to determine the performance of such gradient coils are the magnetic field linearity and magnetic field gradient uniformity. This research emphasizes on the analysis of the geometrical effect of the conventional Golay-Maxwell pair gradient coils to these two parameters through computer simulation. The results show that the geometrical parameters of θ and d affect Golay coil's magnetic field gradient. Usable volume is improved 50% while gradient strength is increased 11% when θ is 160^0 compared to the original 120^0. The increase of d results in increase of usable volume, which is a maximum of 3374 cm^3 at $0.8r$ but a loss of gradient strength of 36% compared to -0.34 mT/m at $0.2r$. The other geometrical parameters of Golay coil are found not to affect much on the magnetic field gradient generated because of two reasons; the longitudinal sections of Golay coil do not contribute to B_z generation and the outer arcs are just acting as current return paths. For Maxwell coil, the usable volume can be improved until 19196.128 cm^3 when d is $2.0r$ although the gradient value obtained is lower compared to a maximum of -0.066 mT/m at $1.2r$. Application wise, the higher the gradient value and the bigger the usable volume, the better since the resolution can be improved, not to mention, a bigger specimen accomodation. A computer simulation is written fully in Open-source environment and feature variation of output as well as faster vectorized algorithm. The simulation results will definitely provide useful information for gradient coil designers without the need for physical development of prototype.

ABSTRAK

Lingkaran kecerunan medan magnet adalah penting dalam proses untuk mendapatkan isyarat yang jitu dalam pengimejan resonans magnet (PRM) atau resonans magnetik nuklear (RMN) dengan penghasilan kecerunan medan magnet pada paksi x, y dan z. Dua parameter untuk menentukan prestasi lingkaran kecerunan adalah kecerunan medan magnet dan keseragaman kecerunan medan magnet. Kajian in menekankan kepada analisis kesan geometri lingkaran kecerunan konvensional, iaitu Golay-Maxwell, terhadap kedua-dua parameter tersebut menggunakan simulasi komputer. Keputusan menunjukkan bahawa parameter geometri θ dan d menjejaskan kecerunan medan magnet gegelung Golay. Isipadu boleh-guna meningkat 50% manakala nilai kecerunan ditingkatkan 11% apabila θ adalah 160^0 berbanding dengan 120^0 pada asalnya. Peningkatan nilai d mengakibatkan peningkatan isipadu boleh-guna, semaksimum 3374 cm^3 pada $0.8r$ tetapi pengurangan nilai kecerunan sebanyak 36% daripada nilai - 0.34 mT/m pada $0.2r$. Parameter geometri gegelung Golay yang lain didapati tidak memberi kesan yang yang nyata kepada kecerunan medan magnet kerana dua sebab; bahagian melintang gegelung Golay tidak menyumbang kepada penghasilan B_z dan lengkok luar hanyalah berfungsi sebagai sambungan untuk menyempurnakan litar. Untuk gegelung Maxwell, isipadu boleh-guna boleh ditingkatkan kepada 19196.128 cm^3 apabila d adalah $2.0r$ namun nilai kecerunan yang didapati rendah berbanding dengan nilai maksimum -0.066 mT/m pada $1.2r$. Dari segi aplikasi, nilai kecerunan yang tinggi dan nilai isipadu boleh-guna yang tinggi akan meningkatkan resolusi di samping membolehkan penggunaan sampel yang lebih besar. Simulasi komputer ini dihasilkan menggunakan perisian sumber terbuka dan mempunyai ciri-ciri seperti pelbagai pilihan output dan juga algoritma yang lebih cepat. Keputusan daripada simulasi ini pasti dapat memberi maklumat berguna tanpa pembangunan prototaip secara fizikal.

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LIST OF ABBREVIATIONS

NMR	-	Nuclear Magnetic Resonance
MRI	-	Magnetic Resonance Imaging
RF	-	Radio Frequency
ROI	-	Region of Interest
VOI	-	Volume of Interest
DSV	-	Diameter Spherical Volume
VTK	-	Visualization Toolkit

LIST OF SYMBOLS

A	-	Ampere
T	-	Tesla
m	-	meter
mT/m	-	mili-Tesla per meter
mT/m/A	-	mili-Tesla per meter per Ampere
GB	-	Gigabytes
ω	-	Larmor precession frequency
γ	-	Gyromagnetic ratio
μ_0	-	Permeability of free space
I	-	Current
$\mathbf{r_c}$	-	Correlation coefficient
$\overrightarrow{\mathbf{AB}}$	-	Vector from A to B
$\mathbf{\hat{u}_{AB}}$	-	Unit vector of $\overrightarrow{\mathbf{AB}}$
$\overrightarrow{\mathbf{AB}} \bullet \overrightarrow{\mathbf{CD}}$	-	Dot product between vector $\overrightarrow{\mathbf{AB}}$ and $\overrightarrow{\mathbf{CD}}$
$\overrightarrow{\mathbf{AB}} \times \overrightarrow{\mathbf{CD}}$	-	Cross product between vector $\overrightarrow{\mathbf{AB}}$ and $\overrightarrow{\mathbf{CD}}$
$\vec{\mathbf{B}}$	-	Magnetic field (vector)
B	-	Magnetic field (scalar)
B_x	-	$\hat{\mathbf{i}}$ component of magnetic field
B_y	-	$\hat{\mathbf{j}}$ component of magnetic field
B_z	-	$\hat{\mathbf{k}}$ component of magnetic field
B_0	-	Main magnetic field
B_1	-	Oscillating magnetic field/RF pulses
G_x	-	Magnetic field gradient in x direction
G_y	-	Magnetic field gradient in y direction

G_z	-	Magnetic field gradient in z direction
η	-	Magnetic field gradient efficiency
$\triangle_{\%}$	-	Magnetic field gradient uniformity

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CHAPTER 1

INTRODUCTION

1.1 Introduction to Modeling

The concept of modeling has a long history of its own, even before the computer exists. Modeling works before the era of computer, however, were limited to the manual theoretical and mathematical formulations. The theories and formulations, usually, are in ideal forms. By using approximations and assumptions, certain specific cases of the theories can be derived. Of course, the possibility of each theory is wide depending of the total parameters involved. While the mathematical formulation still rule the physics world today, a certain depth of knowledge (and imagination) is required for understanding. Fortunately enough, computer modeling or simulation helps in both "visualizing" the mathematics behind the theories and the calculation of each possible cases. Complex modeling may be a daunting tasks for human but that would not be a problem to a computer. As long as there is enough processing power, the computer will be able to execute any number of iterations. One main shortcoming of computer simulation is the inability to model the continuous functions. The most computer simulation can do is to approximate such functions by representating the continuous functions as discrete or finite functions. Numerical techniques such as numerical differentiation or integration, finite element method and finite difference method provide such representation. Generally, the smaller the steps are, the closer the simulation to the actual phenomenon, but with sacrifice in resources and computing time. When such things happens, parallel computing or clustering is preferred in which the job is distributed among few computers.

1.2 Open Source

Many scientific based software and toolkits are available to aid scientists and engineers in their research. The availability of such software provides useful functions and libraries to cater a wide area of applications. The famous scientific based commercial software includes Matlab, Maple, Electronic Workbench and AutoCAD. These software, without a doubt, come in a complete package as possible. Matlab, for example, has found its way into virtually any area of research; physics, statistics, engineering, to name a few. However, these commercial software share one thing in common, the high price for licensing. A full package of Matlab can cost up to few thousand ringgit. For a medium size of computer lab which consists of 10 to 20 computers, the Matlab installations alone is already pass the tenth thousand mark, not to mention the operating software and others. One more issue involving the commercial scientific based software is the licensing of the research product or outcome. Since the development of the product is based on commercial software, the distribution of the product might be troublesome. Although the research outcome is the effort of the researchers, it is still limited by the commercial licensing. As far as the concept of continuing and collaborative research is concerned, such issue no longer encourage knowledge spreading and sharing, if one do not own a legal copy of the commercial development platform.

Fortunately, there are alternatives to this solutions which is the open source software. Commercial software are known as close source software in which the source code of the software are not available to public. Without the source code, the users are not allowed to modify and distribute the software. Open source software are just direct opposite of this. The source codes of the software are available and can be freely modified and distributed as long as they are compiled under the license of the original software. Any programs developed using such software would not face any modification or distribution issue. In such circumstances, open source software are more communities oriented and the communities themselves repay the open source world by providing patches, updates as well as third party extension to the software. Most open source software are freely available. Examples of such software which are scientific based include Octave and Scilab (Matlab alternatives), Python (open source programming language), as well as VisIt and OpenDX (open source visualization programs). With such powerful software minus the price, scientific researchs take a great step forward, needless to always depending on the commercial software. This research takes the opportunity to hightlight the capability and importance of such software.

1.3 Research Profile

1.3.1 Background of Research

In the field of magnetic resonance imaging (MRI), besides the main magnetic field, B_0, and the radio frequency (RF) subsystem, the magnetic field gradient coils subsystem also play an important role in accurate signal acquisition. The operation of MRI is based on a physical theory known as nuclear magnetic resonance (NMR). In this theory, the spin of nucleus can be altered by manipulating the magnetic field. With the presence of the main magnetic field, B_0, and the magnetic field gradient, $G_x = \partial B_z/\partial x$, $G_y = \partial B_z/\partial y$ and $G_z = \partial B_z/\partial z$, the spin at each voxel (grid point in three-dimensional space) can be uniquely characterized in terms of frequency and phase, according to the Larmor equation and detectable by the RF subsystem. The gradient coil subsystem, therefore, is critical in making sure the magnetic field gradient generated is as linear over as large volume as possible.

1.3.2 Statement of Problem

Two of the important specifications of a gradient coil system are the field linearity and gradient uniformity. As the name suggests, the main purpose of a gradient coil is to generate a linearly varied magnetic field (linearity) along certain axis, in this case, x, y and z axis. Besides being linear along certain axis, the magnetic field gradient generated have to be uniform within an area as large as possible (uniformity). The conventional coils used for x and y axis (also known as transverse gradient coils) are the Golay coil configuration whereas for the z axis (also known as longitudinal gradient coil), Maxwell coil configuration is used. Turner revolutioned the gradient coil design by introducing what is called target-field method [1]. This method generally involve solving a Fourier-Bassel expansion using Fourier Transforms [2]. Further researches import Turner's technique by incorporating stream functions by Sanchez et al. [3], using hybrid optimization method by Qi et al. [4], using finite-element method by Shi et al. [5]. The most recent development in gradient coil design is the three-dimensional toroidal design proposed by White et al. [6]. However, the disadvantage of such methods includes a high level understanding of various mathematical functions since the design method is an inverse problem. Besides, in certain applications, conventional gradient coils are still prefered due to their simplicity [7, 8, 9]. Biot-Savart's Law offers a simpler and faster forward solution to gradient coil design problem, making the whole gradient coil simulation and design process cost and time effective.

1.3.3 Purpose of Research

To map the magnetic field generated by gradient coils with emphasize on field linearity and gradient uniformity.

1.3.4 Objectives of Research

The objectives of the research include:

1. To observe how the coil parameters affect the magnetic field gradient, magnetic field linearity and magnetic field gradient uniformity
2. To develop a user friendly, open source and freely distributable magnetic field calculation program
3. To provide valuable information to gradient coils designers without physical prototype development

1.3.5 Significance of Research

The research has come out with a user-friendly program to calculate and map the magnetic field generated by the conventional gradient coils used in MRI and NMR. Therefore, this will provide valuable data to coil designers and researchers without physically constructing the whole gradient coils themselves, reducing cost and time in general. Furthermore, those who use this program do not have to go through complex mathematical equations for them to calculate the generated magnetic field. By utilizing open-source software, this program can be freely distributed to promote knowledge sharing and modification to suit their needs. Since the magnetic field calculation in the program is based on Biot-Savart's Law for finite length current segment, the same algorithm can be used to calculate magnetic field generated by any current carrying conductor as long as the conductors can be divided into a series of finite length segment. This will surely solve the unavailability of analytical Biot-Savart's formulations to calculate the magnetic field generated by current carrying coils at points of interest.

1.3.6 Scope of Research

This research focuses on computer simulation of the magnetic field generated by conventional unshielded gradient coils. Both the Golay coil and Maxwell coil have been modeled and their generated magnetic field and gradient were simulated and mapped accordingly. The field linearity and gradient uniformity of the generated magnetic field were calculated and mapped using some of the definitions suggested by Shi et al. [5], Di Luzio et al. [10] and Bowtell et al. [11]. The effect of coil parameters to field linearity and gradient uniformity have been investigated. The research solved problem in a forward manner rather than most of the gradient coil design methods which are based on inverse problem solving. Besides assisting gradient coils designers, the outcome of the research also provide a complete investigation of the geometrical parameters of the gradient coil.

1.3.7 Methodology of Research

Biot-Savart's Law will be used in the research to simulate the magnetic field generated by the conventional gradient coils. Golay coil and Maxwell coil are two of the well-known gradient coils used in conventional system [12]. By refering to the design, the gradient coils are divided into a series of finite length current segment. Using Biot-Savart's Law for finite length current segment, the calculations in this simulation are iterated and the generated magnetic field are summed up. The results are visualized appropriately in two-dimensional or three-dimensional contour plot. Data has been extracted from the output of the simulation for suitable statistical analysis and tabulated.

1.4 Summary

From the information, the conventional gradient coils were modeled accordingly. Suitable research methodologies were utilized to match the intentions of the research and come out with relevant results. Conclusions are then drawn from the results and discussions. All these will be discussed in the next few chapters.