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Magnetic field analysis for low frequency electrodynamic wireless power transmission

Guillaume de STEINTE MARESVILLE¹, Michael DOSOL¹, Adrien MOREL¹

¹SYMME, Université Savoie Mont-Blanc, Annecy, France

Corresponding author e-mail: guillaume.de-sainte-maresville@univ-savoie.fr

Abstract—Electrodynamic wireless power transfer systems consist in sending power to an electrodynamic receiver with a low frequency magnetic field. This paper presents a model for the magnetic field emitted by the coil, that serve as the small and low-frequency emitter. Based on previous research, the proposed model allows the analysis of both single and two-coil systems in various configurations. The magnetic field and the related gradient are computed and help in determining the best configuration for wireless power transmission. The findings from this study can be used to guide the design and optimization of coils for electrodynamic wireless power transmission applications.

Index Terms—coil, magnetic field, magnetic gradient, wireless power transfer, electrodynamics

I. INTRODUCTION

Wireless Power Transmission (WPT) has gained significant attention in situations where traditional cables cannot be used for energy transfer, such as in in-vivo systems, moving devices, and distant sensors. According to IEEE standards [1], the magnitude of the magnetic field used for WPT is closely related to its frequency, with very low frequency magnetic fields (≤ 100 Hz) allowing for much larger field magnitudes (≥ 0.1 mT) compared to high frequency fields (≥ 10 kHz).

WPT has found diverse applications in modern industries, including powering implantable medical sensors or actuators through conductive media like human tissues [2], as well as through metal walls in submarines, aeronautical [3], and aerospace industries [4]. In order to efficiently transmit energy through conductive medias, researchers have proposed the development of Electrodynamics WPT (EWPT) systems (Fig. 1) operating at low or very low frequencies (10-100 Hz). These systems utilize a coil as the power transmitter and a piezoelectric (PE) beam as the receiver. The power transmitter generates a time-varying magnetic field, while the receiver consists of an oscillating magnet attached to the beam, which strains the beam inducing voltage across the piezoelectric electrodes.

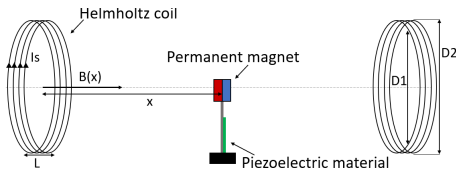


Fig. 1. Schematic of the EWPT system

One critical aspect of EWPT is the magnetic field emitted by the transmitter coil, as maximizing the received energy requires optimizing the magnetic field over distance. This paper presents a model for the coil that allows for the optimization of power transmitted from the coil to the PE transducer. The model is developed for both one-coil and Helmholtz coils systems, providing insights into the behavior of magnetic fields in these configurations.

II. ONE COIL SYSTEM

A. Theoretical model

The magnetic field model of a large coil can be found based on Biot-Savart law. The on-axis magnetic field is given by (1), as detailed in [5] :

$$B_x(x) = \frac{\mu_0 N I_S}{2L(D_2 - D_1)} \left[(L + 2x) \ln \left(\frac{A_1}{A_2} \right) + (L - 2x) \ln \left(\frac{A_3}{A_4} \right) \right] \quad (1)$$

Where $A_1 = D_2 + \sqrt{D_2^2 + (L + 2x)^2}$, $A_2 = D_1 + \sqrt{D_1^2 + (L + 2x)^2}$, $A_3 = D_2 + \sqrt{D_2^2 + (L - 2x)^2}$, $A_4 = D_1 + \sqrt{D_1^2 + (L - 2x)^2}$, $I_S(A)$ is the current in the coil, N is the number of turns, μ_0 is the air permeability, L is the length of the coil, D_1 and D_2 are the inner and outer diameters of the coil and x is the distance between the coil and the receiver.

The on-axis magnetic gradient can be analytically obtained by deriving the magnetic field.

The angle Θ between the magnet axe and the magnetic field axe has an influence on how the power is transferred. When $\Theta = 90^\circ$ (resp. $\Theta = 0^\circ$), the magnetic field induces a torque (resp. a force) on the beam, which depends on the magnetic field amplitude (resp. magnetic field gradient). As explained in [5], the expressions of the induced force and torque on the mechanical receiver are:

$$|\vec{\tau}| = m B_x(x) \quad (2)$$

$$|\vec{F}| = m \frac{dB_x(x)}{dx} \quad (3)$$

Where $m = |\vec{m}|$ is the magnitude of the magnetic moment.

B. Emitted magnetic field and gradient

As shown in Fig. 2, in the case of a single coil, the emitted on-axis field is maximized in the center of the coil and quickly decreases with distance. The magnetic field gradient reaches its peak after a few cm and decreases for larger transmission distances.

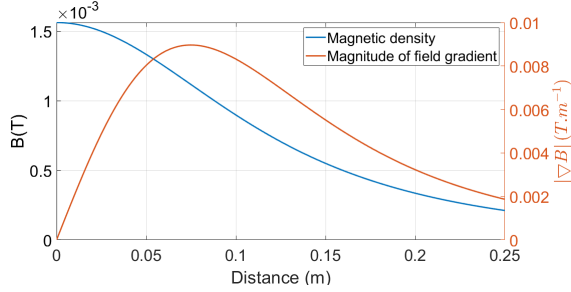


Fig. 2. Theoretical magnetic field density and magnitude of field gradient. The coil parameters are 124 turns, 287 mm inner diameter and 311 mm outer diameter. The input current is 3 A.

III. THEORETICAL MODEL OF HELMHOLTZ COILS

Helmholtz coils are made with 2 coils aligned on the same axis. The distance between both coils can vary and their current can have either the same or opposite sign.

A. Helmholtz coil modeling

The resulting magnetic field produced by Helmholtz coils can be expressed from (1), by adding the magnetic fields of the two coils:

$$B_{x,tot}(x) = B_{x,1}(x) + B_{x,2}(x - x_2) \quad (4)$$

With x_2 being the distance between the two coils. Note that the magnetic field gradient with Helmholtz coils can also be obtained with the same method.

B. Simulated magnetic field

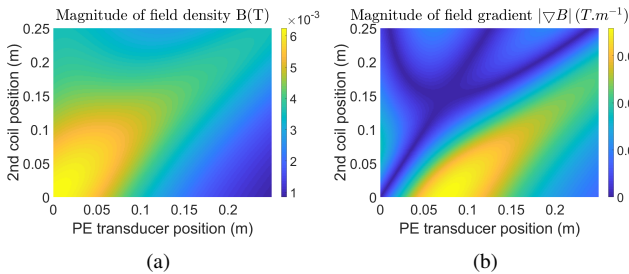


Fig. 3. Amplitudes of (a) Magnetic field and (b) field gradient. The coil parameters are 124 turns, 287 mm inner diameter and 311 mm outer diameter. The input current amplitudes are +3 A for both coils.

In case of same currents polarity, the resulting magnetic field is the sum of both magnetic fields. As shown in Fig. 3(a), the magnetic field is maximized when the PE transducer is halfway between the coils and if the distance between coils is around half of the coil radius. As a matter of example, when

$x_2 = 30$ cm, the field is maximized for a coil-emitter distance of 15 cm. However, in this configuration, the magnetic field gradient is null (Fig. 3(b)). This shows that this configuration (with same coil currents polarity) should be used to maximize the magnetic field (torque mode) but not to maximize the magnetic gradient (force mode).

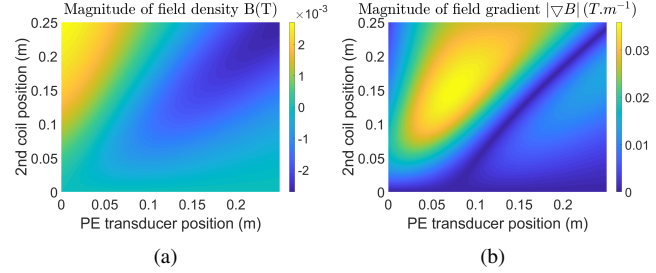


Fig. 4. Amplitudes of (a) Magnetic field and (b) field gradient. The input current amplitudes are +3 A and -3 A.

When coil currents have opposite polarity, the resulting magnetic field is the subtraction of both fields. This case is not optimal for maximizing the magnetic field, Fig. 4(a) shows that the magnetic field is weak and become a little stronger close to the first coil when the second is more than 10 cm away. Despite low field amplitudes, this configuration is of great interest to maximize the magnetic field gradient (Fig. 4(b)). The maximal value is reached when the PE transducer is midway of the coils and the distance between coils is equal to half of the radius of one coil.

This example illustrates that the best possible configuration is to put the PE transducer halfway between coils. The optimal choice of the coil currents polarity depends on the orientation of the receiving magnet (torque or force mode).

IV. CONCLUSION

This paper presents models of electromagnetic transmitter for EWPT. The comparison between single and two coils systems studied in this paper indicates that the two-coil transmitter is more effective, but requires to choose same of different current polarity for the coils, depending on the receiving magnet orientation. Experimental validation of these models is currently underway. Furthermore, these models are currently being utilized to develop a genetic algorithm aimed at designing the optimal coil power transmitter for EWPT. These results will be presented during the conference.

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