CORA Cork Open Research Archive
Cartlann Taighde Oscailte Chorcaí

Title	Frequency dependence of loop antenna H-Field in free-space
Authors	Su, Zhen;O'Callaghan, Brendan;Kumar, Sanjeev;O'Flynn, Brendan;Barton, John;Bulja, Senad;O'Hare Daniel;Buckley, John L.
Publication date	2022-10-26
Original Citation	Su, Z., O'Callaghan, B., Kumar, S., O'Flynn, B., Barton, J., Bulja, S., O'Hare, D., and Buckley, J. L. (2022) 'Frequency Dependence of Loop Antenna H-Field in Free-Space', The 19th RIA/URSI Research Colloquium on Radio Science and Communications, Dublin, Ireland, 26-27 Oct.
Type of publication	Conference item
Link to publisher's version	https://www.ria.ie/19th-riaursi-research-colloquium-radio-science-and-communications
Download date	2025-07-18 05:26:22
Item downloaded from	https://hdl.handle.net/10468/14172

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Frequency Dependence of Loop Antenna H-Field in Free-Space

Zhen Su, Brendan O'Callaghan, Sanjeev Kumar, Brendan O'Flynn, John Barton,
Senad Bulja, Daniel O'Hare, John L. Buckley
Tyndall National Institute, University College Cork, Cork, Ireland, zhen.su@tyndall.ie

***Abstract*—This paper investigates the effect of frequency on the magnetic field (H-field) strength at a specified distance from a single turn transmitting (T_X) loop antenna in free-space. The H-field of a T_X loop antenna in the Near Field (NF) region can be estimated using Biot-Savart's Law (BSL). However, the BSL method is only valid for DC current flow and does not consider the effects of frequency on the H-field strength. This work introduces the frequency-dependent Antenna Near Field (ANF) method reported in the literature and compares this method against the BSL method and EM simulation results. It is shown that the ANF method can estimate the H-field magnitude with an error of less than 5% when compared with finite-element-methods (FEM). In addition, the ANF method computes in a fraction of a second, whereas the FEM method takes several minutes to compute.**

***Index Terms*—Antenna near field, inductive coupling, wireless power transfer, Biot-Savart's law, magnetic field, loop antenna.**

I. Introduction

Wireless power transfer (WPT) using near-field inductive coupling between two coils (transmitting and receiving) can enable many applications in various areas such as Radio Frequency Identification (RFID) [1], [2], Near Field Communication [3] and Biomedical Implants [4]. Near field inductive coupling has the advantage of being able to provide high Power Transfer Efficiency (PTE) [4] but requires close separation between the transmitting (T_X) and receiving (R_X) coils. The PTE performance of a near-field inductively coupled system in free-space can be estimated by first calculating the magnetic field (H-field) strength resulting from current flow in a T_X loop antenna [5]. The frequency of operation is one of the key parameters that determine the optimal PTE of a near-field inductively coupled WPT system [6], [7].

For low-frequency applications, Biot-Savart's law (BSL) is typically used to describe the H-field strength due to a DC current flowing through a T_X loop antenna in free-space [3], [5], [8], [9]. One drawback of this method is that BSL describes the H-field generated by a DC current and does not take into account the effects of frequency on the H-field strength. The ANF method can be used to overcome this limitation [10]. This work aims to investigate the effects of frequency on the magnetic field distribution of a radiating loop antenna. This analysis is based on the near-field inductive coupling between two loops T_X and R_X, in Fig. 1.

Using auxiliary vector analysis on the reader antenna in the near-field regime [10], a simplified magnetic field expression at the R_X antenna location is given in this paper.

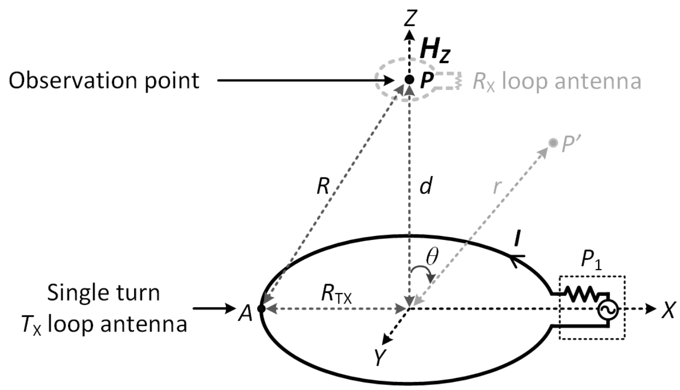

Fig. 1. Near-Field inductive coupling between two loops in free-space, denoted T_X and R_X.

This magnetic field formula contains an operation frequency factor. The magnetic field strength of a single loop is calculated using both the ANF and BSL methods, and the results are compared. In addition, the magnetic field strength for varying frequencies are also compared.

This work analyses the frequency-dependent H-field calculation using the ANF method and compares it with the BSL and EM simulation methods, in terms of accuracy and computation time.

II. Theory

Fig. 1 shows a single turn T_X loop antenna placed in free space with a radius denoted by parameter R_{TX}. Parameter P' represents an arbitrary observation point in free-space and is defined by the distance r from the centre of the T_X loop antenna to the observation point P' as well as the angle θ between the centre of the loop and point P'. For this work, the observation point is defined as point P and is positioned along the positive Z-axis (θ = 0°) as shown in Fig. 1. Port P_1 provides a sinusoidal excitation for the loop antenna and the resulting current I generates a H-field vector quantity denoted H_Z that is orthogonal to the plane of the coil along the Z-axis and can be observed at point P. The H-field at point P can be estimated using the BSL method by assuming that the current flowing through the loop is a steady current $I = I_0$. BSL can be written in integral form as:

$$H = \frac{1}{4\pi} \int_{loop} \frac{I\vec{dl}\ \times\ \hat{r}}{r^2} \qquad (1)$$

In Eq. (1), I denotes the DC current flowing in the loop antenna, $\vec{dl}$ refers to a differential length of the loop antenna and $\hat{r}$ is a unit vector in the direction of P'.

The H-field magnitude along the positive z-axis from the frequency-independent BSL can then be derived from Eq. (1) to be:

$$H_Z = \frac{I_0}{2} \frac{R_{\mathrm{TX}}^2}{R^3}. \tag{2}$$

where, $R = \sqrt{R_{\mathrm{TX}}^2 + d^2}$. The H-field magnitude at the centre of the T_{X} loop antenna can be simplified to

$$H_{Z0} = \frac{I_0}{2R_{\mathrm{TX}}}. \tag{3}$$

The above BSL method has the disadvantage that it does not consider frequency effects on the magnetic field strength. An alternative approach is the ANF method [10], [11] that calculates the frequency-dependent H-field strength passing through point P.

The antenna near-field method is an alternative method used to calculate the H field of the loop in the near field by using the auxiliary vector potential method [11]. The effective magnetic field strength is the r component that orthogonally penetrates through the R_{X} loop and the formula is given as in [10].

$$\begin{aligned} H_r(r,\theta) = {} & \frac{k(kR_{TX})^2 I_0 \cos\theta}{2i} e^{-ikR} \\ & \times \sum_{m=1}^{\infty} \sum_{n=0}^{2m-1} C_{mn}^2 \frac{\left[\frac{k^2 R_{\mathrm{TX}} r \sin\theta}{2}\right]^{2m-2}}{(kR)^{2m+n}}. \end{aligned} \tag{4}$$

In Eq (3) the following parameters are defined; $k = 2\pi/\lambda_G$ where λ_G is the guided wavelength in the propagation medium ($\lambda_G = \lambda_0$ for free-space).

In Eq (3), C_{mn}^2 is a series expansion coefficient [10] and is given by Eq. (4).

$$C_{mn}^2 = mC_{mn}^1 = \frac{1}{(2i)^n} \frac{(2m+n-1)!}{(2m-n-1)!n!} \frac{(-1)^m}{[(m-1)!]^2}. \tag{5}$$

In this discussion, it is assumed that the T_{X} and R_{X} loops are concentric, i.e. the elevation angle is $0°$. In this case, the effective H-field at point P is oriented along the positive Z-axis and can be described using Eq. (6).

$$H_Z = \frac{k(kR_{TX})^2 I_0}{2} e^{-ikR} \left(\frac{i}{(kR)^2} + \frac{1}{(kR)^3} \right). \tag{6}$$

Eq (6) can be further simplified to Eq. (8):

$$H_Z = \frac{k^3 R_{TX}^2 I_0}{2} e^{-ikR} \frac{1}{(kR)^3} (ikR + 1). \tag{7}$$

$$H_Z = \frac{(R_{TX})^2 I_0}{2R^3} e^{-ikR} (ikR + 1). \tag{8}$$

A. Comparison

Comparing Eq.(2) and Eq.(8), the two H-field expressions derived from both Biot-Savart's Law and the Antenna Near-Field method have both similarities and differences. Both methods agree that the maximum H field of the loop antenna appears at the centre of the loop and that the H-field strength drops with increasing distance along the z-axis between the observation point and the centre of the loop. Moreover, the factor kR will tend to zero at low operation frequencies. In this case, as $kR \approx 0$, Eq. (8) can be approximated as Eq. (2). However, when the operation frequency increases, the factor $(ikR+1)$ becomes significant. In this case, the H-field strength calculated by the two methods will be different.

To facilitate a comparison, the above expressions for the BSL and ANF methods were coded and solved in MATLAB [13].

III. RESULTS AND DISCUSSION

A. Simulation Model

As shown in the inset of Fig. 2, an EM model for a single-turn T_{X} loop antenna was developed to validate the H-field frequency dependence obtained from the analytical expressions in Section II. The loop antenna comprises a perfect electrical conductor (PEC) of width $w = 1$ mm with a radius $R_{\mathrm{TX}} = 100$ mm and was excited with a discrete port with impedance $Z_s = 50\,\Omega$ over a frequency range of 1 MHz to 500 MHz using Ansys HFSS [12].

B. Results and Discussion

The graph in Fig. 2 plots the normalized H-field versus frequency at observation point P. The normalised H-field strength is the H-field strength divided by the H-field at the centre of the T_{X} loop, as shown in Eq. (9):

$$\text{Normalized H-Field} = \frac{H_z}{H_{z0}}. \tag{9}$$

As expected, the normalized H-field is frequency invariant for the BSL method. In contrast, the ANF method shows a frequency dependence similar to EM simulations. Fig. 2 also plots the % error between the ANF and EM methods. It is observed that the ANF method estimates the H-field magnitude with an error of less than 5% over the specified frequency range, that is limited by the self resonant frequency of the T_X loop antenna. Note also that on a computer (with a 64 GB RAM, 3.41 GHz 4 Cores i7 processor and a 64-bit operating system), the simulation time for the ANF method is a fraction of the time compared to the EM finite element method, as shown in Table I.

TABLE I
COMPUTATION TIME OF ANF AND EM SIMULATION METHODS.

Computation Method	Computation Time
EM Simulation	567 s
Antenna Near Field	7.92 ms

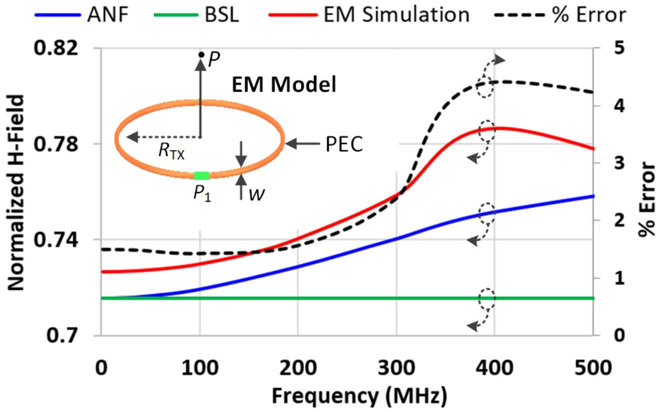

Fig. 2. EM model (inset) and normalized H-Field and % error vs frequency. Note that % error $= 100 \times (H_{EM} - H_{ANF})/H_{EM}$, where H_{EM} and H_{ANF} are the normalized H-fields associated with the EM and ANF methods respectively.

IV. CONCLUSION

This work analyses the Biot-Savart Law and Antenna Near-Field method (ANF) to investigate the effect of operation frequency on the magnetic field from a reader loop antenna. This paper provides a simplified closed magnetic field expression for the H-field due to a loop antenna and discusses the calculated magnetic field difference between the ANF and traditional BSL method. A single turn loop antenna is simulated using HFSS and the normalized H field calculated from both methods are compared with simulations to verify the concept. Results show that the ANF method is a more accurate technique for H-field analysis as it considers the effect of operation frequency on the H-field strength.

ACKNOWLEDGMENT

The authors would like to acknowledge the funding support of MCCI (Microelectronic Circuits Centre Ireland) funded by Enterprise Ireland and the IDA under grant No. EI-MCCI-2020-09-WPIMD as well as Science Foundation Ireland under Grant 12/RC/2289-P2-INSIGHT, 13/RC/2077-CONNECT and 16/RC/3918-CONFIRM which are co-funded by the European Regional Development Fund (ERDF) under Ireland's European Structural and Investment Funds Programmes 2014-2020.

REFERENCES

[1] V. Chawla and D. S. Ha, "An overview of passive RFID," *IEEE Communications Magazine*, vol. 45, no. 9, pp. 11-17, 2007.

[2] Z. N. Chen, C. K. Goh, and X. Qing, "Loop antenna for UHF near-field RFID reader," *in Proceedings of the Fourth European Conference on Antennas and Propagation*, 2010: IEEE, pp. 1-4.

[3] D. Paret, "Antenna Designs for NFC Devices." *John Wiley & Sons*, 2016.

[4] A. Ibrahim and M. Kiani,"A figure-of-merit for design and optimization of inductive power transmission links for millimeter-sized biomedical implants," *IEEE transactions on biomedical circuits and systems*, vol. 10, no. 6, pp. 1100-1111, 2016.

[5] K. Finkenzeller," RFID handbook: fundamentals and applications in contactless smart cards, radio frequency identification and near-field communication." *John Wiley & Sons*, 2010.

[6] A. S. Poon, S. O'Driscoll, and T. H. Meng, "Optimal frequency for wireless power transmission into dispersive tissue," *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 5, pp. 1739-1750, 2010.

[7] D. K. Freeman and S. J. Byrnes,"Optimal frequency for wireless power transmission into the body: Efficiency versus received power," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 6, pp. 4073-4083, 2019.

[8] L. Huang, A. Murray, and B. W. Flynn, "Optimal design of a 3-coil wireless power transfer system for deep micro-implants," *IEEE Access*, vol. 8, pp. 193183-193201, 2020.

[9] A. K. RamRakhyani, S. Mirabbasi, and M. Chiao, "Design and optimization of resonance-based efficient wireless power delivery systems for biomedical implants," *IEEE transactions on biomedical circuits and systems*, vol. 5, no. 1, pp. 48-63, 2010.

[10] D. H. Werner,"An exact integration procedure for vector potentials of thin circular loop antennas," *IEEE Transactions on Antennas and Propagation*, vol. 44, no. 2, pp. 157-165, 1996.

[11] C. A. Balanis, "Antenna theory: analysis and design." *John Wiley & sons*, 2016.

[12] ANSYS HFSS. Accessed: Aug. 25, 2022. [Online]. Available: https://www. ansys.com/products/electronics/ansys-hfss

[13] MATLAB version 9.13. Accessed: Oct. 10, 2022 [Online] Available: https://uk.mathworks.com/products/matlab.html