Research Journal of Applied Sciences, Engineering and Technology 5(5): 1578-1582, 2013
DOI:10.19026/rjaset.5.4907
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: July 12, 2012 Accepted: August 28, 2012 Published: February 11, 2013

Research Article

Simulation of Magnetic Resonance for Wireless Power Transfer

[1]Liang Zhao and [2]Yangjie Liu
[1]Department of Humanities and Law, Northeastern University, Block 11, 3
Wenhua Road, Shenyang 110819, China
[2]Department of Electrical and Electronic Engineering, Nanyang Technological University,
Block S1, 50 Nanyang Avenue 639798, Singapore

Abstract: André Kurs *et al*. (2007) in *Science* 317, 83 titled Wireless Power Transfer via Strongly Coupled Magnetic Resonances, proposed a feasible scheme to near-field transfer electric energy. Here in this report we take note of our simulation on COMSOL 4.1.085 to repeat his counterpart in Chapter 4 of his master thesis. Due to huge requirement on memory size, my simulation fails to align with Kurs', but basic steps and setup instructions are given. Very importantly, every scholar with electromagnetic background would simply take this as magnetic inducing current in closed loops, exactly as we did. Yet, this imparts more essence on resonance. A look into coupled-mode theory will find this takes advantage of near-field magnetic field to transfer energy. A transformer, a true product of magnetic induction, if simply detached by a distance would greatly reduce its transfer efficiency, whereas magnetic resonance DOES NOT! So this is more than only magnetic induction. Although coupled-mode theory is still not physical enough to illustrate readers, neither does magnetic induction in Maxwell's equations give its simple picture! Coupled-mode theory perhaps is a simple way out quantitatively and mathematically.

Keywords: Magnetic resonance, simulation, technology, wireless power transfer

INTRODUCTION

The growth in the use of cordless hand-held electronic appliances in recent years is explosive and stimulating interest in wireless power sources. Only electromagnetic energy is suitable for most applications. Radiative transfer of electromagnetic energy is limited by absorption and scattering in the atmosphere and needs a direct line of sight between the source and the application. However, now the bio-friendly behavior of inductively coupled resonators basing on reducing the interaction with biological and other environmental objects with almost purely dielectric properties is widely used in RFID transponders. Nonradiative inductive coupling between high-frequency circuits within near-field zone has been an attractive option for wireless power transfer applications (Urzhumov and Smith, 2011).

For all the time, redundant wires of miscellaneous electrical devices within our life have brought us a great deal of inconveniences. Therefore, a simple scheme (Kurs, 2007) proposed to avoid such troubles stands out brightly, which makes use of magnetic induction to maneuver power transfer in wireless way-electric power transfers through induction from magnetic induction between two isolated loops. Here in this paper, we try to report some simulation work pertaining to magnetic energy transfer between coupled coils to better understand its principle vividly and shed some light on setup technique on COMSOL simulation for magnetic energy transfer.

To retrieve parameters in coupled-mode theory, we solve eigenvalue problem from physics interface of Electromagnetic Wave (EMW) in Radio Frequency (RF) module. According to Lossy Eigenvalue Calculation in documentation in COMSOL 4.1 interface (COMSOL, 1998-2010), eigenvalue is defined as:

$$\lambda = \delta + j\omega = \delta + j2\pi\upsilon \tag{1}$$

in which real part represents damping and υ in imaginary is eigen frequency. Thus quality factor is $Q = \omega/2|\delta|$. So -i*2*pi*9.9 MHz has to be indicated in blank of search for eigenvalues around.

A single isolated coil:

For a single self-resonant coil:

Step 1: As Kurs described, solve eigenvalue of surrounding air of a single coil. Apply its surface with Perfect Electric Conductor (PEC). After that, several eigenvalues (de facto, only

---

Corresponding Author: Yangjie Liu, Department of Electrical and Electronic Engineering, Nanyang Technological University, Block S1, 50 Nanyang Avenue, 639798, Singapore

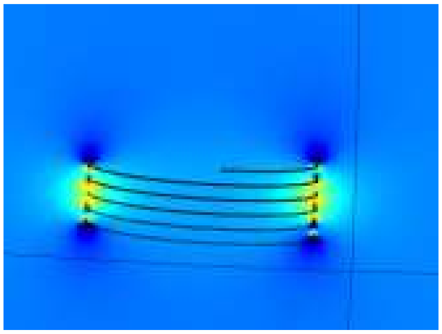

Fig. 1: Z component of magnetic field of one coil

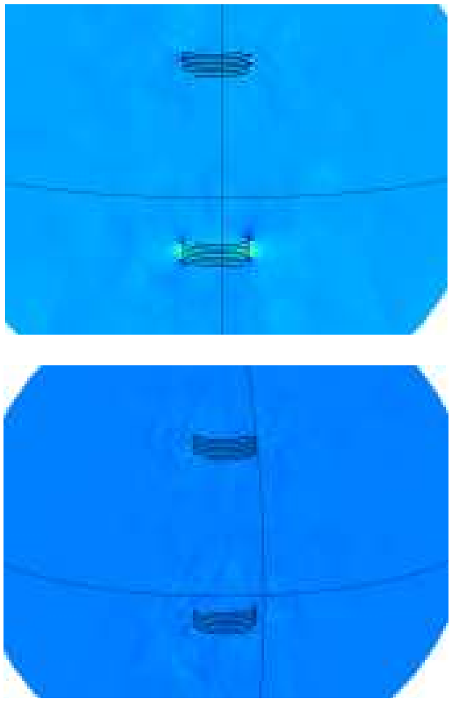

Fig. 2: Z component of magnetic field of two resonant coils, Even and odd modes

eigenfrequency, no damp value or say zero damp) corresponding to 1.033e7Hz, are obtained. But at this circumstance, only z part of electric field is observed in similar plane to Fig. 1, which was magnetic field instead. In fact, in our simulation here, magnetic field is all zero in whole geometry space. Notice, scattering boundary condition at outer boundary of the sphere solution domain, does not work here, we simply replace it with PEC condition. For this step, both zero magnetic field and non-damp are inconsistent with Kurs' narration, which is beyond my consideration. We doubt that his old version, no higher than version 3.3a, does not align with our 4.1 version, albeit not very believably. However, radiation quality factor is possible to obtain from Kurs' theory method to Eq. (3.6) in Chapter 3. This factor formula should be able to assist to guide experiment trials more efficiently.

Step 2: Switch PEC at single coil's surface into impedance boundary condition. Be sure to indicate permeability, permittivity and electric conductivity according to air's property rather than copper's, or else simulation turns out to err. At this step, magnetic field is capable to demonstrate itself (Fig. 1) but eigen frequency is far more less than 1e7 Hz, which is due to the sphere radiussr, not large enough to waive scattering effect of outer boundary. However, our computing resource cannot treat it soon enough-roughly speaking, ideal mesh setups requires more than 24 GB memory to finish it in expectable duration. If, with enough times of trials to increase outer boundary radius, are we able to get reliable eigen frequency and relevant quality factor Q directly from eigenvalue solver. In order to acquire quality factor parameter, another method mentioned in reference torfcoil.mph, is to use frequency domain study to investigate lump port impedance vs frequency. However, Kurs did not indicate that they have used this one.

Two coupled coils: Still with PEC or (possibly, Perfect Magnetic Conductor as document of COMSOL, but we do not do this temporarily) condition on outer boundary surface, and Impedance Boundary Condition on both coil-surfaces, even and odd modes are demonstrated in Fig. 2. Again hereby, a much less than enough sphere radius and a coarser than normal mesh is adopted to expedite calculation process. Therefore in derived values under results, we see all "emw.Qfactor"s behave less than 10, inconsistent with Kurs' result again. But I am convinced an accurate quality factor and thus frequency splitting κ from Eq. (2.8), are able to be reached given much more CPU time.

Magnetic induced current: On the other hand, eigenvalue problems simply need mathematical method to expedite physics calculation process. A possible way out perhaps more physical is to directly calculate induced current density based upon a specified current density distribution in space, using magnetic Field Module (MF) in time-dependent study. File output 8coupled-mf.mph contains study described above but wanting concrete closed loop geometry. I have succeeded in inducing current in a Helmholtz coil in file helmholtz-coil-indop0time.mph.

Summary of simulation: To summarize this report, we have documented simulation detail of my simulation. To achieve Kurs' simulation result:

- A radius of outer boundary has to be fixed only when another radius any larger does not incur eigen frequency variance.
- Then eigen frequency f_0, radiative quality factor Qr, quality factor Q, and even frequency split κ (only this needs to simulate on two coupled coils) are feasible, of course at the price of very huge CPU time.

In the case of self-resonant coil, the roughest mesh ever is to divide domain 2 (helix coil) into meshes as small as 10-20*α (α stands for wire radius), and domain 1(the rest domain except copper coil in the whole sphere) may lose to a mesh of 100*α or so. But keep in mind that when using EMW physics interface to solve eigenvalue problem, the real solution domain is solely air domain (domain 1).

Since whole simulation part does not appear at all in Reference (Kurs *et al*., 2007) we believe this is not a must-to-do job. To obtain parameters above, only coupled-mode theory (Kurs, 2007) is adequate.

It is vital to argue again hereby that this energy transfer does not impart the same physics process as a conventional transformer does. A look into coupled-mode theory will find this takes advantage of near-field magnetic field to transfer energy. To explain the concept of near field more deeply, we have to keep in mind that to validate near-field coupling, distance between two coils have to be maintained within order of several wavelengths for resonance frequency. Whereas, coupled-mode theory perhaps is a simpler way out quantitatively and mathematically than near-field theory, because energy in concept does makes sense in a more abstract way to interpret our world physically, in which a couple-mode theory justifies it as a form of wave energy instead of that of electromagnetic field. Anyway, the latter will certainly inspire people to investigate more deeply by instrument of near field theory.

EXTENSION DISCUSSION AND REMARKS

Metamaterial-enhanced coupling between magnetic dipoles: Inspired by this simple but critical idea, Urzhumov and Smith (2011) derived an optimal power transfer when nonradiative coupling between conductive coils occur. With a simple time-harmonic circuit formulation to treat all interaction process between coils and uniaxial anisotropic medium, they showed an efficiency of power transfer with the slab, one order of magnitude higher than free-space one. Although in our multi-coil case, coupled-mode theory seems to serve the last resort in simple theory, a simple situation of only single-coil loops enable their formulation. As Urzhumov pointed out, other than radiation flux in far field, ratio between electric and magnetic fields can be suppressed, justifying magnetic dipole antenna a possible bio-friendly alternative for wireless transfer of electromagnetic power. However, a three-dimensional magnetic (ideal) point dipole behaves not so convenient to adopt since Transverse Magnetic (TM) wave component of magnetic field is different from near field Transverse Electric (TE) by an order of $(d/\lambda)^2$, which is substantially small under long-wave limit. Thanks to bold trial of negative-and-anisotropic-permeability idea, it leads its way to give rise more autonomy in engineering design. Therefore, it is of value to repeat Urzhumov's circuit model here, in order to unveil possible investigation for coupled magnetic fields of multi-turn coils (Urzhumov and Smith, 2011).

First assume a circular, single-loop of copper wire of radius R. It is clear to write magnetic flux the coil m through all currents in every coil:

$$\Phi_m = \sum_{n=1}^{all} L_{mn} i_{n'}$$

where, coefficients L_{mn} are self-inductances or mutual inductances. Under Faraday' law, induced Electromotive Force (EMF) ε (this nomenclature is perhaps misleading but EMR de facto is not a force but a potential or energy per unit of charge, measured in volts), or equivalently, electric voltage (they differ by almost an electric charge constant) in the m^{th} coil reads.

Providing time-harmonics dependence of currents and fields are satisfied-reasonably if we are aware of the power of Fourier transform. Following this, and taking Kirchhoff voltage law, one gives circuit equations naturally. Hence, one is able to obtain the condition of resonance by expecting denominator of efficient impedance approaches vanity and accordingly concrete calculation of efficiency and figure of merit are known (Urzhumov and Smith, 2011). However, do notice that this linear relation only holds when meta-material wall's contribution to self-inductances of single coils are negligible. Anyway, our world physically exists itself nonlinearly. Another interesting observation Urzhumov pointed is the asymmetry of electromagnetic duality comparing Eq. (50) and (61) therein Reference (Urzhumov and Smith, 2011) the loss tangent of a negative-permittivity slab must be exponentially tiny to cater to comparable coupling efficiency of an engineering-feasible negative-permeability one. One word to explain this eccentricity could be asymmetry of permittivity and permeability in impedance other than trivial comparisons between electrical and magnetic response within natural material.

Hereby we solely express possibility to derive multi-turn coil case of coupled magnetic fields by instrument of Urzhumov's derivation, rather than write it explicitly. It is expected that this simple-but-still physical method digs in further than almost universal coupled-mode theory but still lacks accurate details to compute electromagnetic field in all three-dimension vector's glory, which always pragmatically for the sake of time resorts to brute-force numerical simulation tools such as Finite-Element Method (FEM) or Finite-Difference Time-Domain (FDTD) one. Another lack therein in this Urzhumov's derivation is quantitative analysis of Quality factor (Q). However, it is at least physically reliable to apply this compact circuit model to estimate efficiency of energy transfer. Several overlooked factors have to been included hereafter, to name a few, volume quantity of coil loops and variance upon distance away from near-field source, which may not be implemented easily and may even turn out congruent to near-field theory, not surprisingly at all from universal principle of physics. That is the reason why between theoretical analysis and numerical simulation, a compromise has to be weighed for the sake of feasibility of a physical problem proposed.

Resonantly enhanced near-field imaging: Another further extension of this near-field transfer of electromagnetic energy may inspire the scheme for a device to detect evanescent wave if such a device enable amplify any evanescent existent within near field range. Evanescent wave, carrying infinite-in-theory resolution of object, always enchants academia and thus detectors to it become subsequently challenging in imaging fields. Hence, enhanced near-field imaging obviously deserves attention (Tsang and Psaltis, 2007). To achieve evanescent wave amplification, emerging methods of negative-refractive-index scheme by Sir J.B. Pendry appears derived from relatively elderly achievements of photonic crystal. In fact, negative-refractive-index materials appear due to smart manipulation of natural positive-refractive-index ones. A mimic of solid material structure for light wave, or photonic crystal at least validates this point of view in where they stand. Likewise, similar analogy to quasi-crystals paves a possible headway also. To this end, Mankei Tsang *et al*. proposed a scheme to use dielectric planar waveguides for near-field imaging, and showed transmission of resonant spatial frequency components enhanced by orders of magnitude (Tsang and Psaltis, 2007). Any near field imaging system to amplify evanescent wave emitted or diffracted from object serves as a resonator.

Tsang's scheme, due to high loss of metal for electromagnetic wave, enforced the object extremely close to imaging device, i.e., still within near-field range. It is straightforward to consider conservation of energy to deduce resultant TE evanescent wave explicitly, taking into account that source current density contains direct delta impulse function, a generalized function, so solution to corresponding inhomogeneous vector wave equation for electric field in the method of potential actually vanished everywhere except origin of impulse function. Lack of observation above may easily loose to take solution to homogeneous differential equation mistakenly instead (Tsang and Psaltis, 2007). A very nontrivial feature of evanescent wave lies in its zero energy flux, compatible with its unlimited resolution in theory.

Tsang's scheme focused on evanescent wave to give rise chances to enhance related imaging process, considering impedance matching problem in circuit level, may also inspire people to interpret negative-index permittivity concept deeper. Or, permittivity, the concept quite inclusive of electric response property of a material may reveal itself from perspective of microscopic level. In that way, can one be able to accept negative-refractive index more convinced and persuaded.

CONCLUSION

To sum up this paper, we record basic steps and setup instructions to simulate near field power transfer (Kurs *et al*., 2007; Kurs, 2007) and review recent two extension work of this wireless power transfer. We believe this simple scheme, essential in near field coupling, shall be investigated further to unveil more intricacy of electromagnetic field.

From a perspective of philosophy, we always trust in power of mathematics regardless of concrete physically interpretations. In such a near-field coupling problem, we do have more than one physical theory to account for it. Between these two, circuit model to conceptualize field coupling and near-field angles, convergent results are expected as long as the theory chosen is applicable. However, coupled mode theory seems all-inclusive and at least surpasses domain of electromagnetic theory, and contains dynamical process universally. Henceforth, coupled mode theory may reveal its universal power more in thermodynamics, fluid dynamics and perhaps nonlinear dynamics etc., albeit it derives from a simple Newtonian mechanics problem of a simple string. However, be careful because this expectation of physical theory does not always follow inventor's will and may even become formidable to unveil paradox, when we really need to be conscious of our shortage of making errors or worse, incapability to understand our universe in arbitrary detail.

ACKNOWLEDGMENT

L.Y. would like to thank PrajaktaSabnis, Anna Juhasz and Leong Hon Wai for enlightening guidance on COMSOL simulation and cluster parallel computing. Dr. Hu Liang, at Zhejiang University, P. R. China, proposed this idea to simulate electromagnetic fields for coupled loops. This work was supported by Ministry of Education (MOE), Singapore and High Performance Computing centre (HPC), Nanyang Technological University (NTU), Singapore.

REFERENCES

COMSOL, A.B., 1998-2010. Introduction to COMSOL Multiphysics Version 4.1 6 May 2012 Electromotive Force Wikipedia: The Free Encyclopedia. Wikimedia Foundation, Inc. Retrieved from: http: // en. wikipedia. org/ wiki/ Electromotive_force.

Kurs, A., 2007. Power transfer through strongly coupled resonances. MA Thesis, Dept. Phys., Massachusetts Institute of Technology.

Kurs, A. and A. Karalis, R. Moffatt, J.D. Joannopoulos, P. Fisher and M. Soljačić, 2007. Wireless power transfer via strongly coupled magnetic resonances. Science, 317(5834): 83-86.

Tsang, A. and D. Psaltis, 2007. Theory of resonantly enhanced near-field imaging. Opt. Express, 15(19): 11959-11970.

Urzhumov, Y. and D.R. Smith, 2011. Metamaterial-enhanced between magnetic dipoles for efficient wireless power transfer. Phys. Rev. B, 83(205114): 22.