

Stored Electromagnetic Energy in Bi-isotropic media

Ehrenborg, Casimir; Gustafsson, Mats

2015

Document Version: Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):

Ehrenborg, C., & Gustafsson, M. (2015). Stored Electromagnetic Energy in Bi-isotropic media. Abstract from Progress in Electromagnetics Research Symposium (PIERS), 2015, Prague, Czech Republic.

Total number of authors:

General rights

Unless other specific re-use rights are stated the following general rights apply:

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study

- You may not further distribute the material or use it for any profit-making activity or commercial gain
 You may freely distribute the URL identifying the publication in the public portal

Read more about Creative commons licenses: https://creativecommons.org/licenses/

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 16. Oct. 2025

Session 2P10b SC4: Electromagnetic Energy

Causal Natural Modes, Retro-causal Natural Modes and Minimum Radiation Modes	
Guy A. E. Vandenbosch, Xuezhi Zheng, Victor V. Moshchalkov,	1084
Stored Electromagnetic Energy in Bi-isotropic Media	
Casimir Ehrenborg, Mats Gustafsson,	108
On the Properties of Stored Electromagnetic Energy	
Miloslav Capek, Lukas Jelinek,	1086
A Surface Integral Expression for the Electromagnetic Energy in a Microwave Cavity	
Johan Helsing, Anders Karlsson,	108'
Estimating Antenna Q -factor from the MoM Impedance Matrix	
Doruk Tayli. Mats Gustafsson.	1088

Causal Natural Modes, Retro-causal Natural Modes and Minimum Radiation Modes

Guy A. E. Vandenbosch¹, Xuezhi Zheng¹, and Victor V. Moshchalkov²

¹Department of Electrical Engineering (ESAT-TELEMIC), KU Leuven, Belgium ²Institute for Nanoscale Physics and Chemistry (INPAC), KU Leuven, Belgium

Abstract—In this talk, we discuss three kinds of modes that are crucial to the understanding of a time domain electromagnetic (EM) response. The first targeted mode is called "causal" natural mode. This mode and its corresponding "causal" natural frequency are widely used in the analysis of the transient response of a radiating structure, for example, in the Singularity Expansion Method [1]. They are solutions to the non-standard eigenvalue problem of, e.g., for a microwave antenna, a surface integral equation. In this case, the integral equation only involves the retarded scalar and vector potentials and as a result the electric field at a given time instant t is solely due to an oscillating current in the past. Moreover, since the EM field equations are invariant under time-reversal symmetry, we can reverse the time axis and construct a retrocausal problem for the conventional integral equation. Then, similar to the "causal" natural mode, retro-causal natural modes can be defined when the integral equation is set free of driving force. Last but not the least, we can combine the causal and retro-causal cases to build a new "radiation field" operator. It will be proven that this operator is closely related to the concept of radiated energy [2, 3], and its modes may be defined as "minimum radiation" modes, i.e., where radiated energy and absorbed energy perfectly cancel each other.

- 1. Baum, C. E., "The singularity expansion method," *Transient Electromagnetic Fields*," 129–179, Springer, Berlin, Heidelberg, 1976.
- 2. Vandenbosch, G. A. E., "Radiators in time domain, part I: Electric, magnetic, and radiated energies," *IEEE Trans. Antennas and Propagat.*, Vol. 61, 3995–4003, Aug. 2013.
- 3. Vandenbosch, G. A. E., "Radiators in time domain, part II: Finite pulses, sinusoidal regime, and Q factor," *IEEE Trans. Antennas and Propagat.*, Vol. 61, 4004–4012, Aug. 2013.

Stored Electromagnetic Energy in Bi-isotropic Media

Casimir Ehrenborg and Mats Gustafsson

Department Electrical and Information Technology, Lund University, Box 118, Lund SE-221 00, Sweden

Abstract— Characterizing stored electromagnetic energy is essential in antenna Q calculation [1]. Understanding stored electromagnetic energy as a physical quantity is thus instrumental in characterizing antenna limitations. There exists several expressions for stored electromagnetic energy. In general these expressions give physical results in loss less isotropic media. However, in more complex background materials, such as dispersive or lossy media, these expressions break down, predicting negative energies [2].

This contribution investigates the results of existing stored energy expressions when applied to bi-isotropic media. This is done by implementing the bi-isotropic greens function [3] in the electrical field integral equation in a method of moments code. Stored energy in different types of small antennas will be examined and compared to the stored energy in their equivalent circuit models. The circuit models are generated by Brune synthesis.

ACKNOWLEDGMENT

The support of the Swedish foundation for strategic research is gratefully acknowledged.

- 1. Gustafsson, M. and B. L. G. Jonsson, "Stored electromagnetic energy and antenna Q," Technical Report LUTEDX/(TEAT-7222)/1-25/(2012), Department of Electrical and Information Technology, Lund University, P. O. Box 118, Lund S-221 00, Sweden, 2012, http://www.eit.lth.se.
- 2. Gustafsson, M., D. Tayli, and M. Cismasu, "Q factors for antennas in dispersive media," Technical Report LUTEDX/(TEAT-7232)/1-24/(2014), Department of Electrical and Information Technology, Lund University, P. O. Box 118, Lund S-221 00, Sweden, 2014, http://www.eit.lth.se.
- 3. Lindell, I. V., A. H. Sihvola, S. A. Tretyakov, and A. J. Viitanen. *Electromagnetic Waves in Chiral and Bi-isotropic Media*, Artech House, Boston, London, 1994.

On the Properties of Stored Electromagnetic Energy

Miloslav Capek and Lukas Jelinek

Department of Electromagnetic Field, Czech Technical University in Prague, Prague, Czech Republic

Abstract— A consistent definition of stored electromagnetic energy for non-stationary fields is one of the last fundamental and still unsolved problems of classical electrodynamics. One of the key issues is the potentially infinite total energy within a time-harmonic steady state [1]. There is an ill-defined separation of the total energy into radiated energy and stored energy, where it is assumed that the bearer of the infinity is the radiation [2].

The radiation energy is commonly subtracted separately in the region exterior and interior to the radiator, the boundary being defined by the smallest circumscribing sphere. Many methods are known for determining the radiated (stored) energy outside the circumscribing sphere. All these methods yield qualitatively similar results, although quantitative differences can be found. The situation is more severe in the interior region, since only a few methods are able to take effectively into account the actual shape of the radiator [3, 4]. The differences between the predictions of these methods are moreover qualitative [5].

Besides subtraction of the radiated energy, there are also other techniques for estimating the stored energy, the vast majority of which are inspired by circuit theory [6–8]. However, no matter what concept is used, several fundamental principles should always be kept in mind: e.g., the energy must be positively semi-definite, must be coordinate-independent, must be gauge invariant, and it should be possible to define it locally. Clearly, all the concepts of the stored energy for a dynamic field must also be coherent with those for a static field.

In our talk, we will review all the available concepts that have attempted to determine stored energy. It will be pointed out that all these concepts fail in at least one of the "must have" properties mentioned above. Finally, it will be concluded that no fully consistent definition of stored electromagnetic energy is yet known. This of course raises the question whether the very idea of stored (and radiated) energy is well-posed [9].

ACKNOWLEDGMENT

This work was supported by the Czech Science Foundation under project 15-10280Y.

- 1. Jackson, J. D., Classical Electrodynamics, John Wiley, 1998.
- 2. Collin, R. E. and S. Rothschild, "Evaluation of antenna Q," *IEEE Trans. Antennas Propag.*, Vol. 12, No. 1, 23–27, Jan. 1964.
- 3. Vandenbosch, G. A. E., "Reactive energies, impedance, and Q factor of radiating structures," *IEEE Trans. Antennas Propag.*, Vol. 58, No. 4, 1112–1127, Apr. 2010.
- 4. Gustafsson, M. and L. Jonsson, "Stored electromagnetic energy and antenna Q," Progress In Electromagnetics Research, Vol. 150, 13–27, 2015.
- 5. Capek, M. and L. Jelinek, "Various interpretations of the stored and the radiated energy density," *IEEE Trans. Antennas Propag.*, arXiv: 1503.06752, submitted.
- 6. Grimes, C. A., G. Liu, F. Tefiku, and D. M. Grimes, "Time-domain measurement of antenna Q," *Microwave and Optical Technology Letters*, Vol. 25, No. 2, 95–100, Apr. 2000.
- 7. Yaghjian, A. D. and S. R. Best, "Impedance, bandwidth and Q of antennas," *IEEE Trans. Antennas Propag.*, Vol. 53, No. 4, 1298–1324, Apr. 2005.
- 8. Capek, M., L. Jelinek, P. Hazdra, and J. Eichler, "The measurable Q factor and observable energies of radiating structures," *IEEE Trans. Antennas Propag.*, Vol. 62, No. 1, 311–318, Jan. 2014.
- 9. Mikki, S. M. and Y. Antar, "A theory of antenna electromagnetic near field—Part I," *IEEE Trans. Antennas Propag.*, Vol. 59, No. 12, 4691–4705, Dec. 2011.

A Surface Integral Expression for the Electromagnetic Energy in a Microwave Cavity

J. Helsing¹ and A. Karlsson²

¹Centre for Mathematical Sciences, Lund University, Box 118, Lund 221 00, Sweden ²Electrical and Information Technology, Lund University, Box 118, Lund 221 00, Sweden

Abstract— Today, all high energy particle accelerators use microwave cavities for particle acceleration by means of eigenfields, excited by external sources. In the design process of such cavities it is important to evaluate these eigenfields and the corresponding resonance frequencies. Numerical accuracy is crucial since even small errors in the evaluations may cause a deterioration of the performance of the accelerator. It is convenient, and sometimes necessary, to use normalized electric eigenfields $\mathbf{E}_n(\mathbf{r})$ such that

$$\int_{V} |\mathbf{E}_{n}(\mathbf{r})|^{2} dV = 1 \tag{1}$$

In [1] we developed a high-order convergent Fourier-Nyström scheme for the magnetic field integral equation (MFIE) that can determine the eigenfields and their resonance frequencies with very high accuracy. Since MFIE is a surface integral equation it is very costly to evaluate the volume integral in (1). For this reason we derived a surface integral expression for the normalization integral that is less expensive to evaluate. The integral is expressed in terms of the magnetic vector potential and the scalar electric potential. In this contribution we present an efficient numerical method for the numerical evaluation of the expression for some different types of cavities. We also apply the surface integral expression to the exterior problems of radiation from antennas and scattering of waves from perfectly conducting objects and give an interpretation of the energy it then corresponds to.

ACKNOWLEDGMENT

This work was supported by the Swedish Research Council under contract 621-2011-5516.

REFERENCES

1. Helsing, J. and A. Karlsson, "Determination of normalized magnetic eigenfields in microwave cavities," *IEEE Trans. Microwave Theory Tech.*, 2015 (in press).

Estimating Antenna Q-factor from the MoM Impedance Matrix

Doruk Tayli and Mats Gustafsson

Department of Electrical and Information Technology, Lund University, Lund, Sweden

Abstract— The antenna Q-factor is a useful figure of merit that estimates the antennas bandwidth [1,2]. One difficult part of determining the antenna Q-factor is to calculate the stored energy of an antenna. A method that can be applied to any small antenna is presented in [3-6]. Where the Q-factor is computed using an in-house solver based on a custom method of moments (MoM) implementation. As this requires writing custom code, it is practical to take advantage of the widely available commercial electromagnetic software that have already implemented the MoM and have additional variety of post-processing capabilities.

In this paper the antenna Q-factor is computed from the numerical frequency derivative of the MoM impedance matrix. The impedance matrix is obtained from the commercial software FEKO [7]. Different Q-factor formulations are presented and used to estimate the Q-factor of antennas. These are then compared with the Q-factor calculated from the derivative of the input impedance [8], and the stored energies.

- 1. Harrington, R. F., Field Computation by Moment Methods, Macmillan, New York, 1968.
- 2. Volakis, J., C. C. Chen, and K. Fujimoto, Small Antennas: Miniaturization Techniques & Applications, McGraw-Hill, New York, 2010.
- 3. Gustafsson, M., C. Sohl, and G. Kristensson, "Physical limitations on antennas of arbitrary shape," *Proc. R. Soc. A*, Vol. 463, 2589–2607, 2007.
- 4. Gustafsson, M. and S. Nordebo, "Optimal antenna currents for Q, superdirectivity, and radiation patterns using convex optimization," *IEEE Trans. Antennas Propagat.*, Vol. 61, No. 3, 1109–1118, 2013.
- 5. Gustafsson, M. and B. Jonsson, "Antenna Q and stored energy expressed in the fields, currents, and input impedance," *IEEE Trans. Antennas Propagat.*, Vol. 63, No. 1, 240–249, Jan. 2015.
- 6. Vandenbosch, G. A. E., "Reactive energies, impedance, and Q factor of radiating structures," *IEEE Trans. Antennas Propagat.*, Vol. 58, No. 4, 1112–1127, 2010.
- 7. Altair, S. A., "FEKO, field computations involving bodies of arbitrary shape, Suite 7.0," Development S. A. (Pty) Ltd., Stellenbosch, 2014, https://www.feko.info/, Retrieved: Nov. 24, 2014.
- 8. Yaghjian, A. D. and S. R. Best, "Impedance, bandwidth, and Q of antennas," *IEEE Trans. Antennas Propagat.*, Vol. 53, No. 4, 1298–1324, 2005.