Huygens' Principle, Maxwell Displacement Current and Nanogenerators for Energy Harvesting

Victor Christianto[1]
Faculty of Forestry
Malang Institute of Agriculture (IPM)
Malang, Indonesia
Email: victorchristianto@gmail.com

Florentin Smarandache
Dept. Mathematics and Sciences
University of New Mexico (UNM)
Gallup, USA
Email: florentin.smarandache@laposte.net

[1] Founder of a renewable energy consultant, http://www.ketindo.com

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Abstract—**In recent years, there is a growing number of proposals to use a novel concept of energy harvesting using nanogenerators. This concept can be used for water wave energy harvesting, wind energy harvesting, but also for self-powered microdevices. This novel concept is based on the reality of Maxwell's displacement current. On the other hand, it is known that Huygens' Principle (HP) contains both the principle of action-at-proximity and the superposition principle. Although the propagation of sharp, non-spreading wave fronts is included in Huygens' (1690) original formulation, it can be left out without touching those principles. HP for Maxwell's equations is discussed in terms of the Helmholtz-decomposed fields and currents.**

Keywords—Huygens' principle, Maxwell electromagnetic theory, displacement current, triboelectric nanogenerator, piezoelectric nanogenerator

I. INTRODUCTION (*HEADING 1*)

Huygens' Principle (HP) contains both the principle of action-at-proximity and the superposition principle. Although the propagation of sharp, non-spreading wave fronts is included in Huygens' (1690) original formulation, it can be left out without touching those principles. The formulation of HP by means of the Chapman-Kolmogorov equation (following Feynman 1948) comprises both versions and overcomes misunderstandings like "Huygens' principle is not exactly obeyed in Optics" (Feynman 1948) and "HP is incompatible with Green's functions" (Johns 1974). This way,

HP applies not only to the propagation of light, but also to heat and matter diffusion which can be described through explicit linear differential and difference equations, respectively. HP for Maxwell's equations is discussed in terms of the Helmholtz-decomposed fields and currents.[10]

In the meantime, in a series of recent papers, Wang discusses possible applications of a novel concept for energy harvesting called triboelectric nanogenerators. Self-powered system is a system that can sustainably operate without an external power supply for sensing, detection, data processing and data transmission. Nanogenerators were first developed for self-powered systems based on piezoelectric effect and triboelectrification effect for converting tiny mechanical energy into electricity, which have applications in internet of things, environmental/infrastructural monitoring, medical science and security. In this paper, we present the fundamental reasoning of the nanogenerators starting from the Maxwell equations.[1]

In the Maxwell's displacement current, the first term gives the birth of electromagnetic wave, which is the foundation of wireless communication, radar and later the information technology. Our study indicates that the second term in the Maxwell's displacement current is directly related to the output electric current of the nanogenerator, meaning that our nanogenerators are the applications of Maxwell's displacement current in energy and sensors. By contrast, electromagnetic generators are built based on Lorentz force driven flow of free electrons in a conductor.[2]

It appears to us that the only way to figure out the reality of Maxwell's displacement current is either to measure it with capacitor [8], or use it for nanogenerators [2]. In other words, it seems possible that future nanogenerators will expose the hidden reality behind displacement current, or may be a new term needs to be added. Therefore, in the present paper we will discuss an extended version of Maxwell's equations based on Huygens' Principle. It is shown that there is new term for displacement current.

II. SEVERAL DIFFERENT INTERPRETATIONS OF DISPLACEMENT CURRENT

Our discussion starts from the fundamental Maxwell's equations that unify electromagnetism[2]:

$$\begin{aligned} &\nabla \cdot B = 0 (MagneticGauss), \\ &\nabla \cdot D = \rho_f (Gauss), \\ &\nabla \times E + \partial_t B = 0 (Faraday), \\ &\nabla \times H - \partial_t D = J_f (Amperecircuitallaw), \end{aligned} \quad (1)$$

Where the electric field E; the magnetic field B; magnetizing field H; the free electric charge density ρ_f; the free electric current density J_f; displacement field D,

$$D = \varepsilon_o E + P.$$

(2)

In fourth equation of (1), the second term in l.h.s. of the equation is the Maxwell's displacement current defined as

$$J_D = \partial_t D = \varepsilon_0 \frac{\partial E}{\partial t} + \frac{\partial P}{\partial t}.$$

(3)

The displacement current was first postulated by Maxwell in 1861 [1], and it was introduced on consistency consideration between Ampere's law for the magnetic field and the continuity

equation for electric charges. The displacement current is not an electric current of moving free charges, but a time-varying electric field (vacuum or media), plus a contribution from the slight motion of charges bound in atoms, dielectric polarization in materials. In Eq. (3), the first

component in the displacement current gives the birth of electromagnetic wave, which later being taken as the approach for developing radio, radar, TV and long distance wireless communication.

It can be shown that there is relationship between the second term in the displacement current and the output signal from

nanogenerators, and show the contribution of displacement current to
energy and sensors in the near future. [2]

In this paper, we briefly mention two applications of displacement current:[2]

(1) Piezoelectric nanogenerator, where the displacement current from the media polarization is:

$$J_{Di} = \frac{\partial P_i}{\partial t} = (e)_{ijk}\left(\frac{\partial s}{\partial t}\right)_{jk}. \quad (4)$$

(2) Triboelectric nanogenerator, where the displacement current can be expressed as:

$$J_D = \frac{\partial D_z}{\partial t} = \frac{\partial \sigma_I(z,t)}{\partial t} = \sigma_c \frac{dz}{dt}\frac{d_1\varepsilon_0/\varepsilon_1 + d_2\varepsilon_0/\varepsilon_2}{\left(d_1\varepsilon_0/\varepsilon_1 + d_2\varepsilon_0/\varepsilon_2 + z\right)^2}.$$

Nonetheless, it is known for experts in classical electromagnetic theory, that there are various opinions concerning the meaning and physical reality of equation (3). For experts, see for instance Marco Landini [4], Jackson [5], and Selvan [7]. Here we will only cite some remarks by Tombe [6], as follows:

a. *Maxwell's original approach*: Maxwell conceived the idea of displacement current in connection with elasticity. He had proposed a sea of molecular vortices to explain electromagnetic phenomena, and those vortices were surrounded by electric particles that acted as idle wheels. His views on displacement current can be read in the introduction to part III of his 1861 paper 'On Physical Lines of Force' (beginning at page 39 in the pdf file) at [1]. Maxwell was never satisfied that his molecular vortex model represented a totally accurate picture, and so his attempt to explain the detailed physical significance of displacement current in relation to the rotational aspect of his molecular vortices was somewhat vague. He seemed to be saying that the force involved in displacement current is a tangential force which alters the state of angular momentum of the vortices, and that electromagnetic radiation is therefore a propagation of fine-grained angular acceleration. The angular momentum H would therefore be at right angles and in phase with the tangential force E. Maxwell added displacement current to Ampère's Circuital Law in order to make it applicable to 'Total Current', but it is clear that he did not intend the applicability of this modified version of Ampère's Circuital Law to be restricted to the vicinity of electric current circuits. His follow up work indicates that he intended it to apply anywhere where electromagnetic radiation exists. There seems to be a popular idea circulating around that Maxwell conceived of displacement current in conjunction with the electric capacitor circuit, but this idea is not found in his original papers. [6]

b. *The Modern Textbook Approach:* The modern textbook approach to displacement current is quite different to Maxwell's approach. It is based on the idea that Ampère's Circuital Law needs to be modified in order to comply with situations, such as that which arises in the capacitor circuit, in which charge density is varying with time. Displacement current is then added to one side of Ampère's Circuital Law as an additional term, but it is added on the basis that it is not a real current. The fact that modern displacement is not a real current means that the Ampère's Circuital Law equation has been unbalanced by virtue of adding a new term to one side only. This approach however creates two problems. First of all, the justification for unbalancing the equation is based on the philosophy that the end justifies the means. That is a highly dubious approach when it comes to interfering with equations that have already been derived in the state that they are in. A closer look at the situation further shows that the additional term does not address the issue which it is said to be addressing.[6]

c. *The Polarization approach:* A current flows in a capacitor circuit. This in turn causes a linear polarization of the dielectric between the capacitor plates which blocks the current flow. Linear polarization is a self restoring elastic effect and it is roughly what Maxwell had in mind for displacement current. Maxwell considered displacement current to differ from free current in that the elasticity of the medium would cause the displacement current to grind to a halt. However, as regards electromagnetic radiation, the displacement in question would have to be an angular displacement as opposed to a linear displacement. And in that regard it is interesting to note that Maxwell's concept of polarization was not the straightforward linear effect that we have in mind. In part III of Maxwell's 1861 paper, he says "I conceived the rotating matter to be the substance of certain cells, divided from each other by cell-walls composed of particles which are very small compared with the cells, and that it is by the motions of these particles, and their tangential action on the substance in the cells, that the rotation is communicated from one cell to another." [1]

To conclude this matter, again allow us to cite Tombe [6]:

> "The modern day displacement current is a highly dubious virtual concept, and it bears no connection to what Maxwell had in mind. Conservation of charge in a capacitor circuit is not an issue which is in anyway addressed by displacement current. Conservation of charge is a hydrodynamical issue that is catered for by Bernoulli's Principle whereby voltage and charge represent pressure and current represents velocity. Charge variation with time is not a matter which is catered for in any respect within the realm of Ampère's Circuital Law. If we wish to add a displacement current term to Ampère's Circuital Law then we must justify it in terms of real current just as Maxwell did."

It appears to us that the only way to figure out the reality of Maxwell's displacement current is either to measure it with capacitor [8], or use it for nanogenerators [2]. In other words, it seems possible that future nanogenerators will expose the hidden reality behind displacement current, or may be a new term needs to be added.

III. HUYGENS' PRINCIPLE AND MAXWELL EQUATIONS

According to Enders [10], Huygens' principle can be applied to rewrite Maxwell equations in complete form, starting with:

$$\begin{aligned} &\nabla \cdot \vec{B}_L = 0 (MagneticGauss), \\ &\nabla \cdot \vec{D}_L = \rho_f (Gauss), \\ &\nabla \times \vec{E}_T + \partial_t \vec{B}_T = 0 (Faraday), \\ &\nabla \times \vec{H}_T - \partial_t \vec{D}_T = \vec{J}_T (Amperecircuitallaw), \end{aligned} \tag{5}$$

It is seen that the Helmholtz decomposition genuinely relates the propagation of electromagnetic waves with the transverse field components only. Its drawback – and, perhaps, reason of low acceptance – consists in the fact that it is not Lorentz covariant, so that it has to be separately performed in each system of reference. The criterion of being compatible with special relativity is, however, not the Lorentz covariance, but the compatibility with the Poincare group (Dirac 1949). [10]

Let us further assume that:

$$\vec{D}_T = \begin{pmatrix} D_x(z) \\ D_y(z) \\ 0 \end{pmatrix}; \vec{B}_T = \begin{pmatrix} B_x(z) \\ B_y(z) \\ 0 \end{pmatrix}; \vec{J}_T = \begin{pmatrix} j_x(z) \\ j_y(z) \\ 0 \end{pmatrix}. \tag{6}$$

Then, the four independent dynamical variables ($B_{x,y}, D_{x,y}$) obey the *complete* set of equations (see *Appendix* for Equation 7).

The above set of equations (7) may be combined with equations (4) and (5) for piezoelectric and triboelectric nanogenerators. Nonetheless, these complete set of equations need to be verified with experiments.

IV. CONCLUDING REMARKS

In recent years, there is a growing number of proposals to use a novel concept of energy harvesting using nanogenerators. This concept can be used for water wave energy harvesting, wind energy harvesting, but also for self-powered microdevices. This novel concept is based on the reality of Maxwell's displacement current. On the other hand, it is known that Huygens' Principle (HP) contains both the principle of action-at-proximity and the superposition principle. Although the propagation of sharp, non-spreading wave fronts is included in Huygens' (1690) original formulation, it can be left out without touching those principles. HP for Maxwell's equations is discussed in terms of the Helmholtz-decomposed fields and currents.

It is our hope that discerning the myth from reality (especially in the context of Maxwell's displacement current) is very important step toward tapping and harvesting energy from the hidden electromagnetic structure in Nature.

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APPENDIX

Equation (7) is as follows:

$$\frac{\partial}{\partial t}\begin{pmatrix} B_x \\ B_y \\ D_x \\ D_y \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & \frac{1}{\varepsilon_0}\frac{\partial}{\partial z} \\ 0 & 0 & -\frac{1}{\varepsilon_0}\frac{\partial}{\partial z} & 0 \\ 0 & -\frac{1}{\mu_0}\frac{\partial}{\partial z} & 0 & 0 \\ \frac{1}{\mu_0}\frac{\partial}{\partial z} & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} B_x \\ B_y \\ D_x \\ D_y \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ j_x \\ j_y \end{pmatrix}.$$