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Maxwell's Displacement Current and Capacitors

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Abstract. ***Displacement current is central to starlight in outer space, yet its theoretical justification in textbooks is confined to the restricted context of the space between the plates of a terrestrial electric capacitor. This article will examine how James Clerk Maxwell originally introduced the concept back in the nineteenth century. The modern textbook derivation will then be explained, followed by a detailed investigation into how displacement current relates to electromagnetic induction and electromagnetic radiation in deep space, far away from any laboratory electrical apparatus.***

Maxwell's Method Using the Background Dielectric Solid

I. Displacement current provides the bridge between Faraday's Law of Induction and Ampère's Circuital Law which enables the derivation of the electromagnetic wave equation. James Clerk Maxwell conceived of the concept of displacement current in the context of the elasticity of the medium for the propagation of light. It is first mentioned in the preamble to Part III of his 1861 paper ***"On Physical Lines of Force"***, **[1]**, and later in that same part it is formally introduced starting with equation **(105)**,

$$\mathbf{E} = -(1/\varepsilon)\mathbf{D} \qquad \textbf{(105)}$$

where **E** is electric field (force per unit charge), **D** is electric displacement vector, and ε is electric permittivity. Maxwell however writes it as $R = -4\pi E^2 h$, where the electromotive force, R, is equivalent to the modern-day **E**, where the constant, $4\pi E^2$, related to the nature of the dielectric, is equivalent to the inverse of electric permittivity, 1/ε, and where the electric displacement, h, is equivalent to **D**. The negative sign implies that **E** is a force of self-restoring elasticity, even though Maxwell introduces it as if it is Hooke's Law, where **E** would be the electromotive force that actually causes the displacement, in which case the negative sign shouldn't ideally be there. The important point though, is that we are dealing with self-restoring elasticity in a dielectric solid, which Maxwell proposes as being the medium for the propagation of light, and the negative sign fits with the concept of self-restoring elasticity, which is the kind of elasticity that is associated with electric capacitors and mechanical springs. Therefore, we will treat the negative sign as being correct and use the symbol $\mathbf{E_s}$ for the induced self-restoring electrostatic force in the dielectric solid. Displacement current itself, being the time derivative of the electric displacement, h, then appears as dh/dt in equation **(111)** in the 1861 paper. In modern vector format, equation **(111)** would be familiar in the form,

$$\partial\mathbf{E_s}/\partial t = -(1/\varepsilon)\partial\mathbf{D}/\partial t \qquad \textbf{(111)}$$

Maxwell however writes it as $dR/dt = -(4\pi E^2)dh/dt$. Hence Maxwell's original displacement current is $dh/dt = -1/(4\pi E^2)dR/dt$ (or $\partial\mathbf{D}/\partial t = -\varepsilon\partial\mathbf{E_s}/\partial t$).

In 1864 when Maxwell carried this result into electromagnetic induction, he was carrying it into a field, which rather than involving the recoil type elasticity of a capacitor, actually involved the inertial elasticity that is characteristic of an inductor or a fly-wheel. This would have required the removal of the negative sign in the displacement current, but it seems that the negative sign was swiftly removed anyway in the next equation.

Maxwell's Errors of Addition

II. Having invented the concept of displacement current in conjunction with the elasticity of a dielectric solid, Maxwell immediately made a crucial mistake, although this mistake had no bearing on the substance of his reasoning regarding the existence of displacement current in the first place. The mistake was in connection with Ampère's Circuital Law. Prop. XIV in Part III of the 1861 paper, begins by referring away back to equation **(9)** in Part I of that same paper. This is Ampère's Circuital Law which Maxwell derived hydrodynamically within the context of a sea of tiny aethereal vortices. Note that he didn't derive Ampère's Circuital Law within the context of the dielectric solid. It would seem as though Maxwell used a different medium for his electromagnetic theory than he did for his elasticity theory, but on reading Part III carefully, we note that the sea of aethereal vortices of Parts I and II simply morphs into the dielectric solid. It's left to the reader to assume that he is dealing with a single medium that exhibits dual characteristics. This is an important area where Maxwell was not entirely clear, especially where later in 1864, in Part VI of his 1865 paper ***"A Dynamical Theory of the Electromagnetic Field"*** **[2]**, he applies the displacement current, which he derived from the dielectric solid in Part III of the 1861 paper, to the electromagnetic theory that he derived in conjunction with the sea of molecular vortices in Part II of that same paper.

Maxwell's crucial mistake was that he added displacement current to Ampère's Circuital Law, ***and he added it as an additional term!*** See equation **(112)** which in modern format is,

$$\mathbf{J} = \nabla\times\mathbf{H} - \varepsilon\partial\mathbf{E_s}/\partial t \qquad \textbf{(112)}$$

yet conduction current and displacement current are most unlikely to exist at the same point in space. Displacement current is a particular kind of electric current and not something to be considered as a separate term in Ampère's Circuital Law. Then on top of this mistake of adding displacement current to Ampère's Circuital Law, ***he adds it to the wrong side!*** He adds it to the $\nabla\times\mathbf{H}$ side of the equation instead of to the electric current side. Hence when we bring displacement current across to the electric current side of the equation, it now has a positive sign. Had we wanted $\mathbf{E_s}$ to represent an induced electromotive force of self-restoring elasticity, then a positive sign in the displacement current would be wrong since the internally induced $\mathbf{E_s}$ is a back EMF working against the externally applied $\mathbf{E}$ that would drive a conduction current. This error with the sign continued into the 1865 paper, although in that paper, the nature of displacement current had changed from capacitative to inductive, and so the error with the sign at equation **(112)** turned out to be fortuitous.

The Textbook Method using Capacitor Circuits

III. Maxwell's mistake of summing the conduction current with the displacement current enabled an apparent solution to a problem with Ampère's Circuital Law which never existed, and this is the basis upon which modern textbooks derive Maxwell's displacement current in the absence of Maxwell's dielectric solid. When a capacitor is charging up, the charge density in the plates is varying with time, and so $\nabla\cdot\mathbf{J} = -\partial\rho/\partial t$ as per the equation of continuity of charge at equation **(113)** in the 1861 paper. In modern format, this takes the form,

$$\nabla\cdot\mathbf{J} + \partial\rho/\partial t = 0 \qquad \textbf{(113)}$$

Note that Maxwell doesn't actually use the word *'charge'*, instead referring to *free electricity*. The equation of continuity seems to be incompatible with Ampère's Circuital Law, $\nabla\times\mathbf{H} = \mathbf{J}$, since the divergence of a curl is always zero, and there is a false belief that by adding Maxwell's displacement current to the conduction current, that this will make everything all correct. The argument is, that by adding the displacement current as at equation **(112)**, we then cancel the fact that the divergence of **J** is $-\partial\rho/\partial t$. Taking the divergence of equation **(112)**, and substituting into equation **(113)** we obtain,

$$-\partial\rho/\partial t = -\varepsilon\partial/\partial t(\nabla\cdot\mathbf{E_s}) \qquad \textbf{(114)}$$

whence,

$$\rho = \varepsilon\nabla\cdot\mathbf{E_s} \qquad \textbf{(115)}$$

which is Gauss's law of electrostatics. This argument, never used by Maxwell himself, is used in textbooks to justify the inclusion of Maxwell's displacement current in Ampère's Circuital Law in the absence of a dielectric medium between the plates of a capacitor, and by extension, in the absence of a dielectric medium anywhere in space at all. It's the modern way of justifying displacement current without having to acknowledge the existence of the *aether*. The argument however fails on three counts.

First of all, when we take the divergence of Ampère's Circuital Law, it's correct that we always get zero. This is because the curl in Ampère's Circuital Law acts on the curl of the *electromagnetic momentum* **A**, also known as the *magnetic vector potential*. The sequence of the operations is $\nabla\times\mathbf{A} = \mu\mathbf{H}$, and then $\nabla\times\mu\mathbf{H} = \mu\mathbf{J}$, where $\mathbf{J} = \rho\mathbf{v}$. This is aether hydrodynamics. The charge density is assumed to be constant in Ampère's Circuital Law and the curl operator is only acting on the velocity and vorticity terms in the aether flow. The aether itself is a fundamental fluid of free electricity not to be confused with the dielectric solid mentioned above. This will be clarified in section **IV** below.

When it comes however to the equation of continuity of charge **(113)**, the opposite is the case. The divergence of $\mathbf{J} = \rho\mathbf{v}$ is derived from its charge density and not from its velocity. The rule that the divergence of a curl is always zero, hinges on the assumption that the curl and the divergence will both be operating on the same function, which in the case of the application to Ampère's Circuital Law, means that the charge density, ρ, has to be constant. The equation of continuity on the other hand concerns time-varying charge density. Therefore, neither Ampère's Circuital Law nor Kirchhoff's First Law (the electric current law) apply to capacitor circuits. The addition of displacement current as derived above and placed on the electric current side of the equation, *with a positive sign*, side by side with the conduction current, therefore creates an imbalance and an absurdity.

The second count as to why the textbook argument is wrong is the fact that since $\nabla\cdot\mathbf{E_s}$ is equal to ρ/ε, where $\mathbf{E_s}$ derives from Coulomb's Law, then since $\nabla\times\mathbf{E_s} = 0$ it follows that a displacement current of the form $\varepsilon\partial\mathbf{E_s}/\partial t$ is incompatible with Faraday's Law when it comes to deriving the electromagnetic wave equation, and this is no good because the main purpose of displacement current is to enable the electromagnetic wave equation to be derived **[3]**, **[4]**. In deriving the electromagnetic wave equation, we use Faraday's Law, $\nabla\times\mathbf{E_k} = -\mu\partial\mathbf{H}/\partial t$ and Ampère's Circuital Law $\nabla\times\mathbf{H} = \varepsilon\partial\mathbf{E_k}/\partial t$, where $\mathbf{E_k} = -\partial\mathbf{A}/\partial t$ and $\nabla\times\mathbf{A} = \mu\mathbf{H}$. Neither $\nabla\times\mathbf{E_s} = 0$ nor $\mathbf{J} = \varepsilon\partial\mathbf{E_s}/\partial t$ play any role in this derivation. A displacement current of the form $\varepsilon\partial\mathbf{E_s}/\partial t$, such as would follow from either Maxwell's method or the textbook method, could not be used in Ampère's Circuital Law because it involves a time-varying charge density, whereas Ampère's Circuital Law assumes a constant charge density. The curl in Ampère's Circuital Law does not operate on the charge density. The correct form of displacement current, $\varepsilon\partial\mathbf{E_k}/\partial t$, will be discussed in more detail in Section **IV** below.

The third count is the fact that a displacement current of the form $\varepsilon\partial\mathbf{E_s}/\partial t$ is reactive only and is restricted to regions where there is an externally applied electric field, such as in the vicinity of a charging capacitor, whereas displacement current's main purpose lies in its involvement with wireless electromagnetic radiation which can travel through deep space, far from any laboratory electrical apparatus. Displacement current therefore needs to propagate on its own momentum. It can't be merely reactive. Maxwell's displacement current, as it occurs in electromagnetic radiation, is a specific version of electric current which arises inside a magnetic field anywhere in space.

Although Maxwell himself was not involved in the fraudulent derivation of displacement current that appears in the textbooks, he did nevertheless inadvertently set the groundwork for it, not because of his actual derivation of displacement current itself using a dielectric solid, but because he added it as an extra term to Ampère's Circuital law, ***and then added it to the wrong side of the equation!***

Another unfortunate by-product of the misunderstandings surrounding the origins of displacement current centres on the symmetry between Faraday's law of electromagnetic induction, $\nabla\times\mathbf{E_k} = -\mu\partial\mathbf{H}/\partial t$, and Ampère's Circuital Law when used in connection with displacement current, as in, $\nabla\times\mathbf{H} = \varepsilon\partial\mathbf{E}_{\mathbf{k}}/\partial t$. While Faraday's law is well understood to mean that a changing magnetic field causes an electric field, the symmetry between the two curl equations leads to the myth that Ampère's Circuital Law, when used with displacement current, means the reverse, as in that a changing electric field causes a magnetic field. This is not so, and Maxwell did not derive displacement current on any such basis. When using displacement current, the two curl equations apply simultaneously to the exact same situation. The correct inference is that while a ***changing magnetic*** field does indeed cause an ***electric*** field, an ***electric*** field causes a ***changing magnetic*** field. The electric field will necessarily be changing too in the circumstances, but primarily, a magnetic field is caused by an electric current which doesn't have to be changing at all.

Electromagnetic Induction and the Correct Method

IV. In Part III of his 1861 paper, when introducing the topic of elasticity, Maxwell stated,

"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." James Clerk Maxwell 1861

It was upon this basis that he derived the equations of time-varying electromagnetic induction in Part II of the same paper, yet no sooner had he introduced displacement current in Part III, than the sea of molecular vortices morphed into an elastic dielectric solid, and displacement current became a linear polarization current in this solid. However, when it came to applying displacement current in Part VI of his 1865 paper ***"A Dynamical Theory of the Electromagnetic Field"*** **[2]**, for the purpose of deriving the electromagnetic wave equation, Maxwell slotted it into the time-varying electromagnetic induction theory which he derived in Part II of his 1861 paper. In this part, the induced EMF in electromagnetic induction derives from the circumferential momentum, **A**, of the tiny aethereal vortices that fill all of space, and according to his 1865 paper, the induced EMF in a changing magnetic field is based on the rotational and inertial type of elasticity that is associated with a fly-wheel, which is a similar principle to that involved in the tiny aethereal vortices of the 1861 paper.

The great importance of the elasticity in these matters lies in the fact that it was the vehicle through which Maxwell was able to import the speed of light into his equations using the famous result of the1855 Weber-Kohlrausch experiment [5]. And so, it must be stated that Maxwell did take quite a liberty in transferring the elasticity of linear polarization in the dielectric solid across into the electromagnetic domain. While he appears to have had no justification for assuming the right to do so, and perhaps didn't even notice the presumption, it can actually be justified if his molecular vortices constitute rotating electron-positron dipoles in which electrons themselves constitute an aether sink, while positrons constitute an aether source [6], [7], [8]. Each tiny molecular vortex then becomes a dipolar vortex where the aether is the fundamental electric fluid from which everything is made. These vortices press against each other with centrifugal force while striving to dilate [9]. Displacement current then becomes the electromagnetic momentum **A**, [10], [11]. In a steady state magnetic field, the displacement current will be a ubiquitous tiny localized circulation of free electricity where $\nabla\times\mathbf{A} = \mu\mathbf{H}$. The magnetic intensity, **H**, is the vorticity of the flow. Intertwined with **H** in the dynamic state is the solenoidal electric field $\mathbf{E_k} = -\partial\mathbf{A}/\partial t$. This is an induced EMF acting transversely to the polar origin of a vortex; hence it obeys the relationship $\nabla\cdot\mathbf{E_k} = 0$. It's the induced EMF of Faraday's law and it will cause the vortex to angularly accelerate such that excess pressurized aether spills over into the neighbouring vortex, causing it in turn to angularly accelerate, and the cycle then continues through space. This is wireless electromagnetic radiation and it constitutes a vortex flow of displacement current **A**, flowing from vortex to vortex through the dielectric sea of molecular vortices [12], [13].

Displacement current is therefore the same thing as the *electromagnetic momentum*, **A**, which Maxwell identified with Faraday's *electrotonic state* and is known today as the *magnetic vector potential*, although Maxwell himself doesn't seem to have made the direct connection. The two equations $\mathbf{E_k} = -\partial\mathbf{A}/\partial t$ and $\nabla\times\mathbf{A} = \mu\mathbf{H}$ are perhaps thee singular most important equations in electromagnetism, since they provide the key to the structure of the luminiferous medium, that structure being a sea of aethereal vortices, as was known to men of old [14].

Displacement current then, rather than being the dielectric polarization current that Maxwell envisaged in his 1861 paper, is in fact a much more subtle flow of aethereal electric fluid lurking in a state of fine-grained circulation in the fundamental fabric of the magnetic field. The reason why Maxwell was able to extend the elasticity of dielectric polarization into the transverse elasticity of his sea of molecular vortices is because when we linearly polarize a dielectric which is comprised of rotating dipoles, the result is that a torque acts on the dipoles causing them to precess. We are therefore dealing with fine-grained rotational elasticity in both capacitors and inductors [15]. In the case of inductors, we are dealing with a transverse elasticity which obeys the simple harmonic relationship $\mathbf{A} = -\varepsilon\partial^2\mathbf{A}/\partial t^2$, and hence from the Faraday equation $\mathbf{E_k} = -\partial\mathbf{A}/\partial t$, the appropriate form for the displacement current in Ampère's Circuital Law is $\mathbf{A} = \varepsilon\partial\mathbf{E_k}/\partial t$. It might be argued that the simple harmonic motion is indicative of a self-restoring elasticity, just like in the capacitative case. However, due to momentum, the oscillations in each vortex involve a loss of energy to their immediate neighbour. This is more like the inertial behaviour of a fly-wheel rather than that of a mechanical spring or a capacitor. In capacitors, we are dealing with fine-grained precessional elasticity blocking the flow of electric current altogether.

When we consider a capacitor circuit in the process of charging up, a magnetic field will initially form around the circuit, including in the space between the capacitor plates. Displacement current of the rotational kind will be involved in the formation of the magnetic field. This will involve the angular acceleration of the tiny vortices that fill all of space, and it will involve these vortices aligning themselves such that their rotation axes form solenoidal magnetic lines of force around the electric current circulation. This is Ampère's Circuital Law which is closely related to the Coriolis force. As the magnetic field expands, the source electric current will experience a reactive impedance from the tiny vortices which are squeezing in on it with centrifugal force from all sides. But this reactance, as like with inertial resistance in mechanics, will not halt the motion (current) or reverse the direction of the motion.

In the space between the capacitor plates however, these tiny vortices, being dielectric will experience a torque which will cause them to precess. This will induce a back EMF which will grind the current to a halt in similar manner to the action of a stretched mechanical spring, and the magnetic field, which is dependent on the current flow for its continued existence, will collapse, giving the current a final surge forwards against the reactance of the capacitor. The magnetic field will have given way to an electrostatic field between the plates of the capacitor. Between the plates of the capacitor, while the magnetic field, **H**, existed, the tiny vortices would have been aligned along their mutual rotation axis, but as the capacitor was in the process of charging, the electric current will have been declining, and this magnetic alignment will have gradually been breaking up as the vortices started to precess, hence scrambling the magnetic field, **H**, and replacing it with an electrostatic field, $\mathbf{E_s}$.

Conclusion

V. Maxwell never mentioned capacitors in conjunction with his invention of displacement current. He did however make a series of addition errors which inadvertently diverted the topic of displacement current into the realms of capacitor circuits. First of all, he added displacement current to Ampère's Circuital law as an extra term, when in fact displacement current, as used in electromagnetic radiation should simply be a particular kind of electric current in the context, rather than an extra term. In later years, it was wrongly believed that Maxwell's displacement current, in its capacity as an extra term alongside the conduction current in Ampère's Circuital law, served to make this law compatible with capacitor circuits when the charge is building up on the plates. This became what seemed to be an ideal way of deriving displacement current without having to acknowledge the existence of *the aether*. Maxwell on the other hand had conceived of displacement current in connection with the luminiferous medium, often referred to as *the aether*.

The argument against the modern textbook method is that Ampère's Circuital law was never intended to apply to capacitor circuits in the first place, and the kind of displacement current derived in this manner is not compatible with Faraday's law of induction, which it has to be if it is to be used in the derivation of the electromagnetic wave equation. Electromagnetic radiation exists everywhere in space as far away as the farthest celestial objects whose existence we can detect. A displacement current of the kind derived in the textbooks could only ever exist in the immediate vicinity of a charging or discharging capacitor, or other charging object, and so it would fail in its main role.

The displacement current that exists in starlight in deep space requires an analysis that is different from both how Maxwell justified it in terms of linear polarization in a dielectric and how the textbooks justify it in terms of conservation of charge in a capacitor. Displacement current is actually an inductive effect which should be derived in conjunction with the sea of molecular vortices that Maxwell had already used earlier in his electromagnetic theory **[16], [17], [18].**

So although Maxwell's original derivation of displacement current was capacitative based, where it should have been inductance based, the irony is, that the problem is nevertheless resolvable with the framework of earlier work that Maxwell had already done in deriving the equations of time-varying electromagnetic induction.

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