Wesley's Explanation of Graneau's Exploding Wires Using Ampère's Law Questioned by Analysis Based upon Usage of Coulomb's Law

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***Abstract*- Wesley supports the claim by Graneau that Ampère's law is able to account for the phenomenon called 'Graneau's exploding wires'. He bases the assumption on the same theoretical model as in an earlier treated case of Ampère's bridge, where he derives the forces involved within the bridge using Ampère's law. He also resolves a problem which he claims Graneau has been unable to treat in a satisfactory way: avoiding infinite expressions for the force when two current elements being infinitesimally close to each other are taken into account. Graneau has also assumed the necessity of including a Lorentz force term, in addition to Ampère's law. The author has, in previous research, proposed Coulomb's law as responsible for all electromagnetic interaction, thus sidestepping both Ampère's law and Lorentz' force law, as in the case of Ampère's bridge. This method appears to be successful also in the case of Graneau's exploding wires, since the Coulomb force may again be interpreted as in the case of Ampère's Bridge. As one may conclude from this description, there is deep confusion about which theory is most suitable, and this renders obvious the need for resolving the conflict.**

The benefit of both Ampère's law and Coulomb's law is that they both imply a force component between collinear currents. However, Coulomb's law is able to predict the breaking of wires, whereas in the case of Ampère's law, some still unknown factors need to be defined. A study of experiments being performed during the last decade shows that the focus of interest has moved from the theoretical foundations behind wire breaks to studying effects related to the breaks, especially Z-pinch effects. The ruptures of wires are treated more like empirical facts when applying high enough voltage. The consequence of giving credit to Coulomb's law in this case will also impact other experiments involving electromagnetic forces, due to the universal nature of Coulomb's law.

Keywords*- *Ampère's Law, Ampère's Bridge, Coulomb's Law, Graneau's Exploding Wires, Wesley's Interpretation of Graneau's Exploding wires, Special Relativity Theory

I. INTRODUCTION

Wesley has analyzed experiments with Graneau's exploding wires, thereby providing quantitative predictions using Ampère's law [1]. Graneau himself describes the situation as composed of a combination of transverse Lorentz forces and a set of longitudinal forces that he termed 'mechanical forces' [2]. The existence of different explanatory models reveals a need for analyzing the phenomenon more thoroughly in order to make a definitive statement concerning the origin of the observed physical effects. This paper focuses on revealing the weaknesses of the models proposed by Wesley and Graneau, simultaneously showing how Coluomb's can be used as a model for predicting measurements. Wesley bases his results on his own interpretation of Ampère's force law, leading to an expression for the tension in a wire [1]. This experiment exhibits vast similarities to Ampère's bridge (Fig. 1), and the exploration of this experiment therefore has the benefit of increasing knowledge about electromagnetic forces between rectilinear currents, as is the case with Ampère's bridge. These experiments constitute a separate class where the Lorentz force law is unable to account for the forces being measured, as observed by Graneau in reference [2] above.

II. THE GRANEAU EXPERIMENTS

Graneau performed his experiments at MIT, and the results have been extensively explored elsewhere [3]. Advanced machinery was used in order to achieve high enough voltages with sufficient endurance for achieving breaks of an aluminum wire of thickness 1.19 mm. A voltage of 56 kV was required to induce a current peak of 5 kA. The extended endurance was attained using an inductance of 1000 μH . The subsequent discharge voltage was approximately 60 kV, and this also caused the temperature to rise by several hundred degrees. The experiment was performed using different shapes of wires: straight wires and semi-circular wires mounted vertically. Graneau claims that the straight wires gave the best evidence for "Ampère

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tensile forces", since the Lorentz forces in this case are expected to be perpendicular to the wire along its entire extension, and therefore only the effect of the Ampère forces would have to be taken into account.

III. DISCUSSION CONCERNING THE EVALUATION OF THE RESULTS

A. Discussion Concerning Evaluation of the Results, Graneau vs. Wesley

Wesley uses the longitudinal forces that have been measured within Ampère's bridge as the fundamental experimental conditions with respect to the concept of Ampère repulsion in the experiment explored in this article [1]. The reason is twofold: firstly, Graneau claims that Ampère repulsion is responsible for the breaking of wires carrying high enough currents. Secondly, Wesley has analyzed the repulsive forces detected within Ampère's bridge when cutting off the wires at two points that are perpendicular to each other [4, 5]. The experimental situations are very similar, which allows him to use the same theoretical analysis, based on Ampère's law. In this specific experiment, he makes reference to the tensile stress needed to break a copper wire as described by Graneau, showing that Ampère's law predicts a result that is of the same order (one fourth). He assumes that the difference between result and prediction may be explained by Joule heating, that is weakening the copper wire. This is understandable, since Graneau also discusses this option in his paper [3]. However, neither he nor Wesley present any evidence corroborating their assumption. Nonetheless, Wesley points to the properties of the broken surfaces, supporting the assumption that Ampère repulsion must be responsible. He claims that Joule heating, if responsible for the breaking of the wires, would result in a greater effect perpendicular to the copper wire, and furthermore that the ends would be ragged, whereas the experiments do not show this at all. He concludes that the clean right-angle breaks support Ampère's law. Wesley has a serious objection to the mathematical method used by Graneau in deriving a theoretical result aimed at corroborating the measurement results, namely that he uses the line integral interpretation Ampère's law [1], which implies infinite current densities at the points, where the two elements of the wire meet each other. His criticism focuses especially on the method that Graneau uses in order to solve the problem, i.e., the introduction of an arbitrary 'fudge factor' using current elements of arbitrary length, so that the result of integration is brought to yield measurement results. Wesley, on his part, solves the problem in the mathematically stringent way by using volume integrals [1].

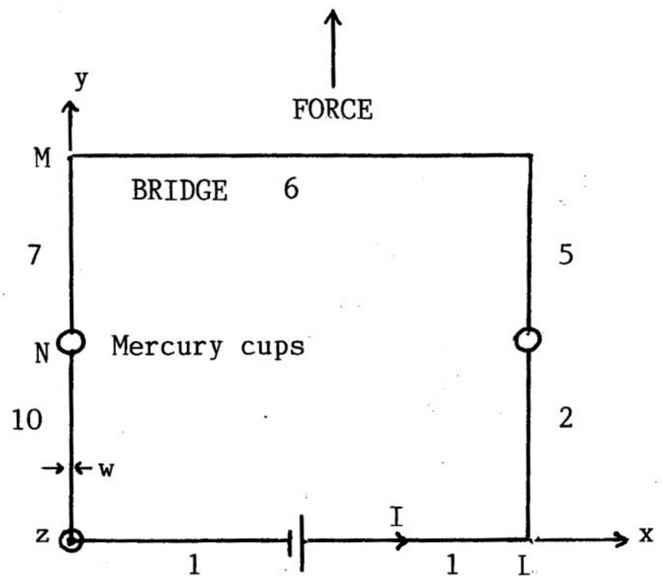

Fig. 1 Model of Ampère's bridge [6]

Graneau uses the argument in favour of Ampère's law that it had been highly appreciated by Maxwell, adding that it had also been widely used for 80 years [3]. There have been several attempts made to link Ampère's law to different parts of today's widely used concepts, including Grassmann's effort to make his law (predecessor to Lorentz force) appear to be consistent with Ampère's law [7, 8] and Maxwell's effort to make his laws do the same by praising Ampère's law. However, in neither case do they provide a relevant reference supporting their claim [9].

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Since Graneau is the physicist who made the fundamental analysis of the Ampère tension within conductors, and Wesley mainly made some additional comments with regard to integration techniques, it seems most relevant to deal with the argumentation put forth by Graneau. He refers to Maxwell as giving his support to Ampère's law, and that passage is cited by Graneau [3]. It is, however, interesting to read what Maxwell himself writes after that passage, namely that he does not understand how Ampère has derived his law, claiming that he must be hiding some vital parts of the process prior to the construction of the law. Neumann [10] also raises questions concerning the experimental basis behind the construction of the law.

B. Ampère's law

Ampère's law for the electromagnetic force between two electric currents is based on his own work, in which he proposes a formulation that agrees with experiment [11]. Some confusion exists on this point, since some later authors, like Jackson [12], ascribe a completely different expression as Ampère's law. The author has in a previous paper [8] formulated Ampère's law as follows:

$$d^2\vec{F}_{ji}{}^{A} = -\frac{\mu_0}{4\pi}\cdot I_i I_j \cdot \frac{\hat{r}}{r^2}\cdot(2(d\vec{l}_i \cdot d\vec{l}_j) - 3(\hat{r}\bullet d\vec{l}_i)(\hat{r}\bullet d\hat{l}_j)) \tag{1}$$

Wesley used instead an expression directly based on Ampère [5]:

$$c^2\vec{F}_A = I_1 I_2 \vec{r}\cdot(-2d\vec{s}_2 \bullet d\vec{s}_1 / r^3 + 3(d\vec{s}_2 \bullet \vec{r})(d\vec{s}_1 \bullet \vec{r})/r^5) \tag{2}$$

Wesley uses Gram weight units. The first term on the right-hand-side in both of these expressions indicates that there will be a force between collinear currents.

C. Numerical Results of Ampère's Bridge Applied to Graneau's Exploding Wires

Using the expression for the force between the two parts of a set of Ampère's bridge that he had derived in other papers [4, 5], Wesley derives an expression for the tensile stress within a copper wire [1]:

$$S = \frac{4T}{\pi d^2} = (\frac{4I^2}{\pi d^2})(0.107 + \ln(D/d)) \tag{3}$$

where

S the tensile stress ($\frac{kgm}{mm^2}$),

T the Ampere tension (kgm)

d the cross-section of the wire (mm)

I the current through the wire (A).

Using the values of the parameters according to Graneau [13], d= 1 mm, L=150 cm, I= 10^4 amp., $D = \frac{2L}{\sqrt{\pi}} = 169cm$, where D is the diameter of the circuit (cm) and L is the length of the wire (cm), he obtains the value of 7.59 kgm for the Ampere tension in the wire. This is equivalent to a tensile stress of $S = 9.66\frac{kgm}{mm^2}$, which he states is about one fourth of the tensile stress needed to break cold copper, but undoubtedly sufficient to break copper weakened by Joule heating.

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D. Derivation of the Electromagnetic Force According to Jonson's Interpretation of Coulomb's Law

The author [14, 15] arrived at values close to those of Wesley, or, in any case with the correct slope of the curve, when analyzing Ampère's bridge using Coulomb's law. This implies that the same statement concerning the validity with respect to the breaking of copper wires must be assumed. The reason is that Wesley in that case was using Ampère's law with the same formula when analyzing Ampère's Bridge [1]. In a recent paper, the author applies the Special Relativity Theory to Ampère's bridge [6]. It is a necessary step, if the intention is to perform a more rigorous analysis of the problem, since in all the cases velocities are involved. Furthermore, the Special Relativity Theory may have consequences for the results. The geometry of Ampère's bridge is also well-suited for dealing with two parallel currents at a short distance from each other, since the problem of leading the current back to its origin has already been solved in a previous paper by the author [16]. Applying the same method as in the recently published paper [6] concerning two parallel currents at a short distance a from each other yields the following expression for an infinitesimal element:

$$\Delta^2 \vec{F}_{12} \bullet \vec{u}_y \cong -\frac{\mu_0}{4\pi} \cdot I_1 I_2 \Delta x_1 \Delta x_2 \cdot \frac{a \cdot (x_2 - x_1)^2}{2r^5} \tag{4}$$

Integrating this expression along the whole line gives accordingly:

$$F_{total} \cong -\frac{\mu_0 I_1 I_2 L}{4\pi \cdot 3a} \tag{5}$$

The Lorentz force for the same case would be:

$$F_{total,Lorentz} \cong -\frac{\mu_0 I_1 I_2 \cdot 2L}{4\pi a} \tag{6}$$

Hence, the force appears to be six times smaller than that predicted by the Lorentz Force Law. Ona can conclude instead that the value of each current has been measured to be $\sqrt{6}$ times less than the current value. This implies that if applying the Special Relativity Theory according to Eq. (5), the currents measured will be a factor of $\sqrt{6}$ times stronger than earlier assumed. Thus, a six times stronger tension will arise in the wire, and the break condition will be exceeded by a wide margin.

IV. OTHER EXPERIMENTS ON EXPLODING WIRES

More recently, other experiments involving exploding wires have been performed. Sinars et al. presented a paper in 2001 [17] that deals with Z-pinch experiments measuring energy deposition, expansion rates for the exploding wire cores and morphology of exploding wires of different materials, but they do not deal with any theory for the tensile stress. They are working more empirically, attaining the breaks but analyzing other features like voltage collapse due to the appearance of plasmas. In another paper (2002), Sarkisov et al. discuss the effect of the polarity of the current for exploding wires in vacuum [18]. The importance for Z-pinch physics is emphasized. Making reference to Gauss's theorem, without any closer derivation, they claim a radial electric force, decreasing with $1/r$ with respect to the wire to be responsible for either the increase or the decrease of the potential barrier in the vicinity of the metal-vacuum interface. However, they do not discuss the basic reasons for the appearance of tensile stress. Again, the tensile stress seems to be regarded as an empirical fact. Another paper, by Sarkisov et al. in 2004, focuses on the metal core in nanosecond exploding wires [19], but the reasons for the tensile stress are still not studied in this case. The topic is treated empirically, and the focus is on the plasma appearing around the wire in connection with the breaks. A later paper, by Das et al. in 2012, discusses the electrical explosion of wire systems with the intention of producing nanopowder [20]. The paper defines some theoretical concepts in order to describe the mechanism, rather than explaining the fundamental reasons for tensile stress. A very recent paper by Sheid et al. focuses on the usage of exploding wires as an ignition source. The reason is that there have been certain disadvantages inherited in connection with dust cloud ignition [21], but this paper still does not treat any fundamental theory for the very explosion of wires. Stephens et al. published a paper in 2012 dealing with surface coated exploding wires [22]. They have been studying the effects of applying an inert insulation on silver wires, which adds a current density of order $1.5 \cdot 10^7 \, A/cm^2$ on a microsecond scale.

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Sinton et al. discuss the conditions for creating arcs by using exploding wires in a 2011 paper [23]. Their focus is on creating extra-long arcs, and they discuss the experimental conditions and present empirical data on the subject. They state that the creation of arcs is due to the plasma that forms in the fragmentation sites as a consequence of the electric breakdown of the gas there. An older contribution to the subject was already made in 1987 in connection with the International Symposium on Electromagnetic Fields in Electric Engineering in Pavia, Italy, by Graneau [24]. What is most interesting in connection with the intentions of this paper is that the authors claim that exploding wires to belong to a special class of experiments that are "conforming with Ampère's law and conflicting Lorentz's", thereby referring to experiments performed by Nasilowski.

To conclude, it appears that after Wesley and Graneau there has been no substantial debate on the tensile stress issue prior to this paper, the emphasis being more on the properties of the plasma and related phenomena.

V. DISCUSSION ABOUT THE THEORETICAL FOUNDATIONS

Wesley discusses the shape of the ruptures of the exploding wires and concludes that, since the breaks always occur under clean straight angles with respect to the wires, this favours an explanation based on the collinear forces that arise according to Ampère's force law [1]. If the breaks were caused by Joule heating instead, this would have given rise to ruptures also in the radial direction, and those have never been observed, according to Wesley. He also points to the fact that radial rupturing would be preferable, if Joule heating were to be the cause, due to the smaller expansion resistance in the radial direction. Other methods of heating until melting, like microwaves, have not given rise to explosions in metal. However, in spite of these arguments, Wesley considers that Joule heating nonetheless contributes to the breaks. What he is opposing is that this alone should be the cause of the ruptures. If Wesley's assumption is correct, the clean right angle breaks observed indicate an impulsive tensile loading in the axial direction. In order to strengthen his argumentation in favour of a tensile loading in the axial direction, he refers to other experiments by Graneau [25], but this time on liquids. Graneau observed that electric arc currents travelling through salt water faced sudden explosions that he was not able to ascribe to Lorentz forces. Instead, Graneau argues that longitudinal forces according to Ampère's law are the cause. Since Coulomb's law is very well corroborated [26], it must seem much more agreeable to favour an explanation based on Coulomb's law, if any such explanation is available. Even better, it has been possible to use Coulomb's law, provided that the propagation delay is taken into account correctly [15] in addition to compensation for the Special Relativity Theory [6]. Furthermore, using this approach yields a prediction of the breaking down of wires which agrees better with the experiment, whereas the use of Ampère's law would require the invention of "unknown" factors in order to explain the discrepancy between theory and results. Ampère's law has been successfully refuted by the author [8], and it has been shown that Coulomb's law is able to account for the forces earlier ascribed to Ampère's law [15]. As regards Ampère's bridge, it is only logical to assume that Coulomb's law must be able to predict the results also in this case, due to the similar properties of the experiment with respect to Ampère's bridge. Coulomb's law predicts a rather similar behaviour of the force within Ampère's bridge as Ampère's law, but the slope of the curve describing the dependence on the thickness of the wire agrees better with experimental measurement [27]. The slope of a curve describing measurements constitutes a good test of the credibility of an assumption that has been made. Finally, Graneau himself is unable to support his own assumption that there exists a combination of the transverse Lorentz forces and a set of longitudinal forces, called by him 'mechanical forces' [2], with any argument. Therefore, this statement cannot be assessed. He does not discuss Joule heating as a potential cause of the breaks.

VI. CONCLUSIONS

Graneau, who has performed the experiments that have been discussed in this paper, has not been able to propose a clear theory exploring the connection between a causal law and the rupturing of the wires. He proposes a combination of the commonly recognized Lorentz forces and another, not precisely defined, longitudinal force, and he does not even touch on the question of the influence of Joule heating. It seems that he has not been able to formulate a comprehensive theory that can be corroborated. Wesley, in turn, relies on one single theory, Ampère's law, as the principal cause behind the rupturing of wires. Making reference to a rather successful usage of Ampère's law in connection with another experiment (Ampère's bridge) involving forces between collinear currents, he assumes that, due to the common features of these two categories of experiments, it is reasonable to also apply Ampère's law in the case of Graneau's exploding wires. The discrepancy between measurements and theory he ascribes to the effects of Joule heating, though he does not precisely describe how this occurs. However, he does not discuss the problem of the straight angle direction of the breaks in spite of the added effects of Joule heating. The other experiments referred to in section IV are not accompanied by any discussion about the theoretical foundations of tensile stress and the ruptures of wires, with the exception of the paper by Graneau [24]. Therefore, a choice has

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to be made between the explanations offered by Graneau, Wesley and by the author. The explanation provided by this paper seems most plausible, since it succeeds in predicting the straight angle breaks by using Coulomb's law. To conclude, the main result of this paper is that it has been successful in eliminating the confusion that has existed thus far concerning the physical law that is to be ascribed to the observed collinear forces between rectilinear currents responsible for the ruptures of wires, known as 'Graneau's exploding wires'. The conclusion to be drawn is that Coulomb's law is responsible, an otherwise very well-corroborated law. This conclusion is supported by references to another experiment that also involves collinear forces, namely Ampère's bridge. Thus, a basis has been laid for the further investigation also of other kinds of experiments involving electromagnetic interaction, especially those where a comprehensive understanding of the observed effects is still lacking.

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