The Repulsive Force Within Ampère's Bridge Explained by Coulomb's Law and Special Relativity Theory, Taking into Account the Effects of Propagation Delay

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***Abstract*-It has been previously proved that the repulsive force between the two parts of Ampère's bridge, measured in experiments performed by Pappas and Moyssides, can be explained by Coulomb's law, if the effects of propagation delay are correctly taken into account. Special relativity theory is also necessary to estimate the extent to which it may affect the result. Otherwise it might be unnecessary to involve special relativity theory in the case of DC currents carried by electric conductors, because the velocities of conduction electrons are usually very small compared to the speed of light. However, in this paper, the force between the two parts of Ampère's Bridge has been calculated, taking into account special relativity theory, particularly the Lorentz transformation which brings about a change in the lengths of moving bodies. The result is that the repulsive force between the two parts of Ampère's bridge remains repulsive, displaying dependence on the thickness of the branches, decreasing with increasing thickness. This was also the case when analysis was conducted without taking into account the special relativity theory. In fact, the predictions are in complete agreement with physical measurements.**

Keywords*- *Ampère's Law; Coulomb's Law; Propagation Delay; Electromagnets; Ampère's Bridge; Lorentz Force; Retarded Action; Special Relativity Theory, Lorentz Transformation

I. INTRODUCTION

Evidence has been presented in several previous papers that refutes the widely-recognized electromagnetic theory [1-5]. One such fundamental law is the law of Lorentz force. A paper in 1997 presented mathematical proofs showing that the law of Lorentz force is unable to explain the repulsive force experienced between collinear currents, as demonstrated in the case of Ampère's bridge [1]. Even Graneau's exploding wires and Hering's pump cause difficulties when trying to use the law of Lorentz force in order to explain the effects that have been registered [6-9]. Assis has also made comments on Ampère's bridge in a book, mentioning that Maxwell has written about Ampère's effort to devise an experiment to verify longitudinal forces between electric currents [10]. The author has applied Ampère's bridge to show that Ampère's law is inconsistent with Biot-Savart's law, even in the case of a closed circuit [11]. This was proposed by Maxwell as a method to prove that they are not equal pointwise [12]. The author thereby also succeeds in disproving an effort by Bueno and Assis to corroborate Maxwell's claim, using Ampère's bridge as an example [13].

The impossibility of explaining the observed forces within Ampére's bridge according to Maxwell's theory [14] necessitates the continued analysis of Ampére's bridge and similar types of experiments involving similar geometric properties, in order to explain this apparent discrepancy between evidence and established theory. Another paper agreed with the discrepancy [1], proposing a return to Coulomb's law in order to determine if this will account for the force within Ampére's bridge [15]. This succeeded, but the task remains to include special relativity theory.

II. EXPERIMENTAL BACKGROUND: THE PAPPAS-MOYSSIDES EXPERIMENTS

In the early 1980s, Pappas and Moyssides performed a series of measurements on sets of Ampère's bridges, which was of especial importance to them, since that experiment had not been performed earlier [14].

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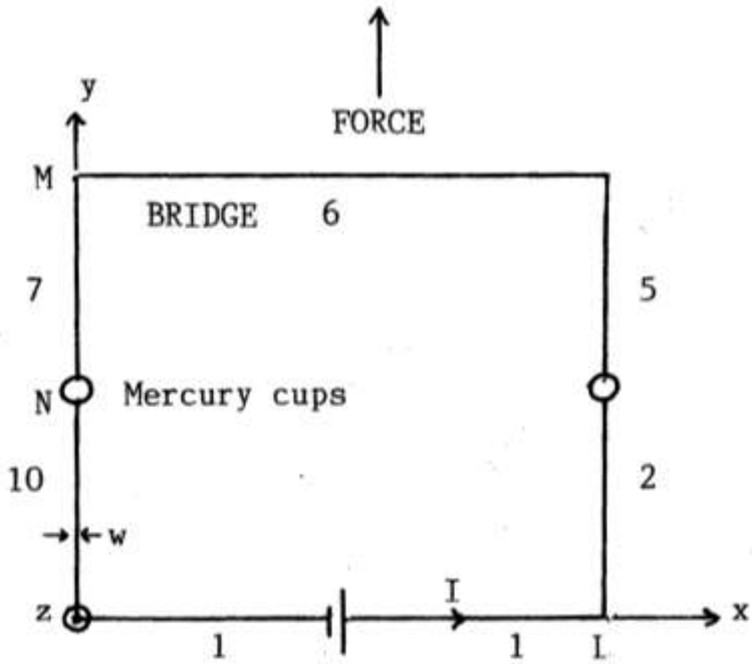

Fig. 1 Simplified model of Ampère's bridge

III. THEORY

A. General

The basic assumption is that Coulomb's law provides a sufficient explanation to the electromagnetic interaction between electric charges, irrespective of the velocities of the conduction electrons, excluding thereby the need for introducing magnetic fields and Lorentz forces. This explains the repulsive force between the two parts of Ampère's bridge that Pappas and Moyssides were able to measure [1]. Their success was the direct result of the introduction of a revised model of propagation delay. In another paper, the deficiencies of customary methods for deriving propagation delay were exposed, and a correct method was introduced [2]. In brief, both currents involved in the interaction provide different propagation delays, dependent on the velocity of the charges. The positive immobile cluster ions cause no direction-dependent inhomogeneity, whereas the mobile conduction electrons do. The varying strength of the field that this induces is able to account for the effects otherwise ascribed to the Lorentz force. Thus far, the special relativity theory has not yet been involved; the extremely low velocities of conduction electrons may deem it unnecessary [16].

As noted above, Coulomb's law is assumed as the basic original force. The effects of propagation delay are then applied, as well as the Lorentz transformation of space.

B. The Electromagnetic Force Between Two Currents

The two currents were analyzed according to Coulomb's law, taking into account the effects of propagation delay and the special relativity theory. The effects of the propagation delay were derived in a paper published in 1997 [1], using a different interpretation from that of Feynman [18] and Jackson [15]. Another paper displayed their fallacies [2]. In the 1997 paper [1], it was crucial to Coulomb's law that the propagation delay was correctly derived, both due to the "sending charges" of the "first conductor" as well as to the "receiving charges" of the "second conductor". Having performed that analysis, it remains to take into account the effects of special relativity theory, particularly the Lorentz transformation of lengths. Because that effect is related only to the relative movements of the two coordinate axes and not to the propagation delay experienced by an observer, straightforward multiplication becomes possible.

An electric current carried by a conductor implies that both the immobile lattice ions and the moving electrons contribute to the force exerted on other charges. If they are embedded in a neighbouring electric conductor that is also carrying an electric current, they interact with both positive lattice ions and moving conductor electrons. This means that four kinds of interaction will take place, each demanding separate mathematical treatment: from positive ions in the first conductor to both kinds of charges in the second conductor, and from the electrons in the first conductor to both kinds of charges in the second conductor. In quadrangle circuits, the two currents appear both parallel and perpendicular to one another.

C. Coulomb's Law: Basic Formulation

Coulomb's law for two point charges can be expressed as follows [16]:

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$$\vec{F} = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^3} \cdot \vec{r} \tag{1}$$

In order to integrate the contribution to the total force between two currents carried by conductors, it is most suitable to use the differential force induced by an incremental segment. Assuming that a one-dimensional conductor is situated in the $x-y$ plane, the incremental force created by a three-dimensional charge element in the x direction can instead be written as follows [1]:

$$\Delta\vec{F} = \frac{\rho_1 \rho_2 \Delta x_1 \Delta x_2 \cdot \vec{u}_r}{4\pi\varepsilon_0 r^2} \tag{2}$$

where

$$\vec{r} = (x_2 - x_1, y_2 - y_1, 0) \tag{3}$$

The force between the two currents will appear as the y -component of the total force, according to the following equation:

$$\Delta\vec{F} \bullet \vec{u}_y = \frac{\rho_1 \rho_2 \Delta x_1 \Delta x_2 \cdot \vec{u}_r \bullet \vec{u}_y}{4\pi\varepsilon_0 r^2} \tag{4}$$

When both conductors are parallel to each other, particularly along the x -axis as shown by lines 1 and 6 in Fig. 1 (above), attractive or repulsive forces between them may be described as the y-component of the force in Eq. (2), also expressed in Eq. (4).

When all charges are stationary, there will be neither a propagation delay nor a relativistic effect due to the Lorentz contraction of one or both coordinates.

D. Method to Derive Propagation Delay

The effects of propagation delay become relevant when the charges are moving, so that the electric field due to a sending charge must be evaluated at an earlier time event than when the field was activated at a distant point. As distance increases, travel time also increases, as was described in previous analysis [1].

The expression for the charge density observed at a distant point when the charge density ρ_1 is due to individual charges moving with velocity $\vec{v}_1$, is given by the following expression:

$$\rho_{1,ret} = \rho_1 (1 - \frac{\vec{v}_1 \bullet \vec{r}}{rc}) \tag{5}$$

which may also be written as:

$$\rho_{1,ret} = \rho_1 (1 - \frac{v_1}{c} \cdot \cos\theta) \tag{6}$$

This charge density expression will also be used when the electrons are studied at the first conductor, but a change of sign will then occur.

In this connection, the traditional interpretation of propagation delay as described by Feynman [18] in his derivation of the Liénard-Wiechert potentials is fallacious [2]. However, there will appear a propagation delay effect with respect to the charges receiving the action, because the greater the distance between these charges and the sending charges, the smaller the charge density to the sender when compared to the simultaneous charge density. Correspondingly, the expression for the charge density observed by the sending charges is given by:

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$$\rho_{2?ret} = \rho_2 (1 - \frac{\vec{v}_2 \bullet \vec{r}}{rc}) \tag{7}$$

which may also be written as

$$\rho_{2,ret} = \rho_2 (1 - \frac{v_2}{c} \cdot \cos\psi) \tag{8}$$

This expression for the charge density will be used when the electrons are being studied at the second conductor, but a change of sign will then occurs.

E. Coulomb's Law, Taking into Account the Effects Of Propagation Delay

The total force between two elements of the respective circuit consists of the sum of the forces due to the four combinations of positive lattice ions and conduction electrons. The first instance is when the electric force due to the positive charges of both conductors is studied. The expression for the force will then represent both sections aligned along the x-axis.

$$\Delta\vec{F}_{+\to+} \bullet \vec{u}_y = \frac{\rho_1 \rho_2 \cdot \vec{u}_r \bullet \vec{u}_y \cdot \Delta x_1 \Delta x_2}{4\pi\varepsilon_0 r^2} \tag{9}$$

The second instance applies to the situation in which the conduction electrons of the first conductor affect the positive immobile ions of the second conductor. This is represented by Eq. (5), with an overall change in sign.

$$\Delta\vec{F}_{-\to+} \bullet \vec{u}_y = \frac{-\rho_{1,ret} \cdot \rho_2 \cdot \vec{u}_r \bullet \vec{u}_y \cdot \Delta x_1 \Delta x_2}{4\pi\varepsilon_0 r^2} \tag{10}$$

The third instance applies when the positive immobile ions of the first conductor exert a force on the conduction electrons of the second conductor, written as:

$$\Delta\vec{F}_{+\to-} \bullet \vec{u}_y = \frac{\rho_1 (-\rho_{2,ret}) \cdot \vec{u}_r \bullet \vec{u}_y \cdot \Delta x_1 \Delta x_2}{4\pi\varepsilon_0 r^2} \tag{11}$$

Finally, the fourth instance applies to the situation in which the conduction electrons of the first conductor exert a force on the conduction electrons of the second conductor, which will yield:

$$\Delta\vec{F}_{-\to-} \bullet \vec{u}_y = \frac{\rho_{1,ret} \cdot \rho_{2,ret} \cdot \vec{u}_r \bullet \vec{u}_y \cdot \Delta x_1 \Delta x_2}{4\pi\varepsilon_0 r^2} \tag{12}$$

These four contributions are combined, keeping in mind the following relationships:

$$I_1 = \rho_1 v_1 \tag{13}$$

$$I_2 = \rho_2 v_2 \tag{14}$$

$$\frac{1}{\varepsilon_0 \mu_0} = c^2 \tag{15}$$

The following expression is obtained for the total electric force between two electric currents carried by conductors [1]:

$$\Delta\vec{F} = \frac{\mu_0 I_1 I_2 \cos\theta \cos\psi \cdot \Delta x_1 \Delta x_2}{4\pi \cdot r^2} \cdot \vec{u}_r \tag{16}$$

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which is valid when the angles between two conductors are chosen arbitrarily. In the case of two parallel conductors:

$$\theta = \psi \tag{17}$$

This expression was successfully able to predict the repulsive force between the two parts of Ampère’s bridge, whereas the Lorentz force was not [1].

F. Coulomb’s Law, Taking into Account the Effects of Special Relativity Theory

The special relativity theory implies that relative movement causes the length of moving objects to decrease, as observed from the laboratory system, thereby utilizing the standard configuration [17]. Hence, the vectors between moving and stationary charges must be adjusted according to this assumption.

Thus, in order to derive more exact expressions to calculate the electric force due to moving charges, all terms containing the distance vector between charges in the expressions above must be modified to incorporate the Lorentz contraction of space [18]:

$$x' = \frac{x - vt}{\sqrt{1 - v^2/c^2}} \tag{18}$$

Some prefer to use the Lorentz factor instead [17]:

$$\frac{1}{\sqrt{1 - v^2/c^2}} \tag{19}$$

Simplifying the calculations by assuming that the electrons carrying both currents are propagating with equal velocity, i.e.,

$$v_1 = v_2 = v \tag{20}$$

Furthermore, Eq. (20) also implies that

$$\gamma(v_1) = \gamma(v_2) = \gamma(v) \tag{21}$$

Some necessary preparations are also necessary prior to performing the integrations, because the denominators of the terms to be integrated make integration in closed form unfeasible, with the exception of Eq. (9). Serial expansion of the denominators in binomial series [19] makes it possible to transform the denominator terms of $(\frac{v}{c})$ embedded in $\gamma(v)$ into numerator polynomials; this will simplify the mathematical treatment.

The Lorentz transformation according to the special relativity theory will then be applied. For practical reasons, the calculations have been separated into two categories: the parts of the conductors interacting with each other being parallel or perpendicular to each other, it should be noted that the Lorentz transformation does not affect the product of charge density and the infinitesimal length element because:

$$\rho = \frac{dQ}{dx} \tag{22}$$

Accordingly:

$$\rho \Delta x = \frac{dQ}{dx} \cdot \Delta x + O((\Delta x)^2) \tag{23}$$

The Lorentz contraction of the dx terms in the numerator and denominator thus cancel out.

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G. Mathematical Treatment of the Concept of 'Infinite Length'

Conductors may be regarded as being of infinite length compared to the rectilinear distance between them. Maxwell previously posited that this analysis is incomplete without taking into account the path along which the respective currents return to their origin, and that the apparent conflict between the theories of Ampère and Grassmann is related to this [20]. What Maxwell did not specify is the mathematical treatment of "infinite length", which must be infinite with respect to a smaller entity in the circuit. The sides of the set of Ampère's bridge in the application of Pappas and Moyssides with sides L and M, respectively, demonstrated a gap between the two branches of the bridge which intersect at two points a. Treating the length of each side as infinite can be mathematically expressed as follows:

$$L >> a \tag{24}$$

and

$$M >> a \tag{25}$$

IV. THE PARALLEL PARTS OF THE TWO CONDUCTORS ALIGNED ALONG THE Y-AXIS

A. Branches 10 and 7, Thin Conductor Approximation

When both branches are situated along the y-axis, this implies necessary changes to the equation for the calculation of force between parallel currents.

In the first instance, when the electric force due to positive charges of both conductors is studied, the expression for the force is as follows:

$$\Delta\vec{F}^{R}_{+\to'+} \bullet \vec{u}_y = \frac{\rho_1\rho_2\vec{u}_r \bullet \vec{u}_y \cdot \Delta y_1 \Delta y_2}{4\pi\varepsilon_0 r^2} \tag{26}$$

where

$$\vec{r} = (0, y_2 - y_1, 0) \tag{27}$$

and

$$\cos\theta' = 1 \tag{28}$$

In the second instance, which applies to conduction electrons of the first conductor affecting the positive immobile ions of the second conductor, the mathematical expression is as follows:

$$\Delta\vec{F}^{R}_{-\to'+} \bullet \vec{u}_y = \frac{-\rho_1(1-\frac{v_1}{c}\cos\theta'')\rho_2 \cdot \vec{u}_{r''} \bullet \vec{u}_y \Delta y_1 \Delta y_2}{4\pi\varepsilon_0 (r')^2} \tag{29}$$

where

$$\vec{r} = (0, y_2 - \frac{y_1}{\gamma(v_1)}, 0) \tag{30}$$

and

$$\cos\theta'' = -1 \tag{31}$$

The sign within the brackets in Eq. (29) thus becomes positive.

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In the third instance, when the positive, immobile ions of the first conductor exert a force on the conduction electrons of the second conductor, it will be expressed as follows:

$$\Delta\vec{F}^{R}_{+\to -} \bullet \vec{u}_y = \frac{-\rho_1\rho_2(1-\frac{v_2}{c}\cos\theta'')\cdot\vec{u}_r \bullet \vec{u}_y \Delta y_1 \Delta y_2}{4\pi\varepsilon_0 (r'')^2} \tag{32}$$

where

$$\vec{r}'' = (0, \frac{y_2}{\gamma(v_2)} - y_1, 0) \tag{33}$$

and

$$\cos\theta'' = \frac{\frac{y_2}{\gamma(v_2)} - x_1}{r''} \tag{34}$$

Finally, in the fourth instance in which the conduction electrons of the first conductor affect the conduction electrons of the second conductor, this will give rise to the following expression:

$$\Delta\vec{F}^{R}_{-\to -} \bullet \vec{u}_y = \frac{\rho_1(1+\frac{v_1}{c}\cdot\cos\theta''')\rho_2(1-\frac{v_2}{c}\cdot\cos\theta''')\cdot\Delta y_1 \Delta y_2}{4\pi\varepsilon_0 (r''')^2} \tag{35}$$

where

$$\vec{r}''' = (0, \frac{y_2}{\gamma(v_2)} - \frac{y_1}{\gamma(v_1)}, 0) \tag{36}$$

The sign within the first set of parentheses is positive, because the currents are opposite to one another.

Adding the four above equations yields the following result for the collinear force between the two parts:

$$\Delta\vec{F}^{R}_{total} \bullet \vec{u}_y = \frac{\mu_0}{4\pi}\cdot\frac{I_1 I_2 \Delta y_1 \Delta y_2}{r^2}\cdot(-1) \tag{37}$$

Utilizing $\vec{r}$ according to Eq. (27):

$$\vec{F}^{R}_{total}(10\to 7) = \frac{\mu_0 I_1 I_2}{4\pi}\cdot\int_{y_1=0}^{N-a} dy_1 \int_{y_2=N}^{M} dy_2 \cdot \frac{-1}{(y_2-y_1)^2} \tag{38}$$

Calculating the integral provides the result, modified to the new limits in the y direction, i.e. M and N instead of L and $\frac{L}{2}$, respectively:

$$\vec{F}^{R}_{total}(10\to 7)\bullet\vec{u}_y = \frac{\mu_0 I_1 I_2}{4\pi}\cdot(\ln\frac{L}{a} - \ln 4) \tag{39}$$

However, since it has been assumed that

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$$L >> a \tag{40}$$

the expression may simplify to:

$$\vec{F}^{R}_{total}(10 \to 7) \bullet \vec{u}_y = \frac{\mu_0 I_1 I_2}{4\pi} \cdot \ln \frac{L}{4a} \tag{41}$$

in the instance in which the conductor is regarded as infinitesimally thin, the small gap of length a is the only variable which contributes to variation of the force. Hence, the force appears to be repulsive to a first order approximation, corroborating the general Pappas-Moyysides experiments.

B. Branches 10 and 7, the Conductors of Non-Vanishing Width and Thickness

In order to attain a more exact result necessitates the recognition that the gap a is much smaller than the width of the conductor w, so that:

$$a << w << L \tag{42}$$

and

$$a << w << M \tag{43}$$

This means that at the branch intersections, volume integrals must be applied to account for the non-vanishing lengths in the two directions perpendicular to the conductors, the x and the z axes, respectively.

This implies that the expression for $\vec{r}$ must be modified accordingly so that Eq. (37) is replaced with

$$\vec{r} = (x_2 - x_1, y_2 - y_1, z_2 - z_1) \tag{44}$$

This in turn implies that the integral equation defining the total force will become more complicated in form.

The expression for the force between branches 10 and 7 may then be expressed as:

$$\vec{F}^{R}_{total}(10 \to 7) = \frac{\mu_0 I_1 I_2}{4\pi} \cdot \frac{1}{w^2 t^2} \cdot \int_{x_1=0}^{w} dx_1 \int_{x_2=0}^{w} dx_2 \int_{z_1=0}^{t} dz_1 \int_{z_2=0}^{t} dz_2 \int_{y_1=0}^{N-a} dy_1 \int_{y_2=N}^{M} dy_2 \cdot \frac{y_2 - y_1}{r^3} \tag{45}$$

Integrating with respect to y_2 and y_1 in this order provides the following intermediate result:

$$\begin{aligned} \vec{F}^{R}_{total}(10 \to 7) = \frac{\mu_0 I_1 I_2}{4\pi} \cdot \frac{1}{w^2 t^2} \cdot \int_{x_1=0}^{w} dx_1 \int_{x_2=0}^{w} dx_2 \int_{z_1=0}^{t} dz_1 \int_{z_2=0}^{t} dz_2 \cdot \\ \cdot \ln \frac{-M + \sqrt{M^2 + A^2}}{N - a - M + \sqrt{(N-a-M)^2 + A^2}} \cdot \frac{-a + \sqrt{a^2 + A^2}}{-N + \sqrt{N^2 + A^2}} \end{aligned} \tag{46}$$

where a variable A is defined, such that

$$A^2 = (x_2 - x_1)^2 + (z_2 - z_1)^2 \tag{47}$$

With close contact between the two branches of Ampère’s bridge, the gap is defined as:

$$a = 0 \tag{48}$$

Constant terms can be excluded from further integration, resulting in the following:

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$$\vec{F}^{R}_{total}(10 \to 7) = \frac{\mu_0 I_1 I_2}{4\pi} \cdot (\ln 2 + \ln \frac{(M-N)\cdot N}{M} - \frac{1}{2w^2t^2} \cdot \int_{x_1=0}^{w} dx_1 \int_{x_2=0}^{w} dx_2 \int_{z_1=0}^{t} dz_1 \int_{z_2=0}^{t} dz_2 \cdot$$
$$\cdot \ln((x_2 - x_1)^2 + (z_2 - z_1)^2)) \tag{49}$$

According to the fact that

$$I_1 = I_2 = I \tag{50}$$

in the case of Ampère's bridge , integration provides the following:

$$\vec{F}^{R}_{total}(10 \to 7) \cong \frac{\mu_0 I^2}{4\pi} \cdot (\frac{4}{3} \cdot \ln 2 + \frac{\pi}{3} - \frac{25}{12} + \ln \frac{(M-N)\cdot N}{M} \cdot \frac{1}{w}) \tag{51}$$

However, there are two equal branches in total, requiring the result to be doubled in order to include the second branch:

$$\vec{F}^{R}_{total} \cong \frac{\mu_0 I^2}{4\pi} \cdot (\frac{8}{3} \cdot \ln 2 + \frac{2\pi}{3} - \frac{25}{6} + 2 \cdot \ln \frac{(M-N)\cdot N}{M} \cdot \frac{1}{w}) \tag{52}$$

However, the thickness of the conductors are given as the cross section d , as follows:

$$d = \frac{2w}{\sqrt{\pi}} \tag{53}$$

Eq. (52) can then be rewritten, so that:

$$d = \frac{2w}{\sqrt{\pi}} \tag{53}$$

$$\vec{F}^{R}_{total} \cong \frac{\mu_0 I^2}{4\pi} \cdot (\frac{8}{3} \cdot \ln 2 + \frac{2\pi}{3} - \frac{25}{6} + 2 \cdot \ln \frac{(M-N)\cdot N}{M} \cdot \frac{2}{\sqrt{\pi} \cdot d}) \tag{54}$$

This integral was previously evaluated by Wesley [21, 22].

C. Contribution to the Total Force from the Other Branches of the Circuits

Using the same method as described above, all the contributions appear to be negligible, expressed by the following:

$$w << L, M, N \tag{55}$$

Maxwell has previously discussed the negligible effects of parts of the conductors at long distances from one another [23], since only in the case where two branches from each conductor come in close contact do the force terms become significant, due to the $1/r^2$ dependence of the force.

Therefore, the result provided by Eq. (54) is a good approximation and valid for the entire circuit.

V. ASSESSMENT OF THE CALCULATIONS

Comparing the theoretical result obtained by Eq. (52) above with real measurements obtained by Pappas and Moyssides [1, 21, 14] provides very good agreement.

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The cross section $d = 1.9mm$ resulted in the measured repulsive force $F = 11.4(gmweight / amp^2) \cdot 10^{-5}$ (predicted: $F = 11.4$). The cross section $d = 3.1mm$ resulted in the measured repulsive force $F = 10.4(gmweight / amp^2) \cdot 10^{-5}$ (predicted: $F = 10.4$).

VI. CONCLUSIONS

The most fundamental result presented in this paper is that Coulomb's Law can be used to calculate the varying repulsive force between the two parts of Ampère's bridge which intersect. Since this repulsive force arises between collinear current elements, the Lorentz force is unable to account for it as the Lorentz force is perpendicular to the currents involved [10]. Hence, the main contribution of this paper is to establish a theory to establish the forces between collinear currents. This contrast with contemporary basic physics, according to which Coulomb's Law can only be applied to electrostatic calculations. To apply Coulomb's Law to electrodynamics, analysis of the propagation of the Coulomb field according to the principle of retarded action was required and to correctly take into account the effects of propagation delay. Further, special relativity must be applied to account for the length contraction that takes place according to the Lorentz transformation when bodies move with a non-vanishing velocity, even though the speed of the electrons carried by a metallic conductor is extremely small [17] compared to the speed of light. The force derived from this method exhibits the same spatial behavior as the Lorentz force, identifying it as a good theory. It is able to explain other electromagnetic phenomena and has so far not been disproved with respect to physical experiments. Coulomb's law represents a well-corroborated law, first derived successfully by Cavendish [15], and as long as it remains able to successfully predict experiments there is no reason to replace it.

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