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INTEGRATION OF THE AMPERE FORCE AND TRIPLED RAILGUN DESIGN

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ABSTRACT. This papers presents an analytical integration for the Ampere's force law. It then makes estimations of the operational characteristics of the railgun based on the Ampere's force law. Operating at a current of 300kA, a 4m long tripled railgun may fire a 1kg projectile reaching an exit speed of 2020m/s (Mac 5.9) with kinetic energy of 2.04MJ. It is estimated that the ohmic loss is just about 3% of the kinetic energy. When the operation of the railgun is analyzed based on the Lorentz magnetic force, there is difficulty in identifying the precise seat of the railgun recoil. In contrast, the analysis done based on the Ampere's force law could precisely specify the seat of recoil of the railgun; it is at the *'empty space'* in the interface separating the atoms of the rails and the atoms of the gun breech. During firing, contrary to expectation, the rails would be under tension and not compression.

1. INTRODUCTION

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The traditional explanation for the working of the railgun is based on the Lorentz magnetic force law and Maxwell's electromagnetism. There is an alternative explanation of the working of the railgun based on the Ampere's force law, a law that has been largely ignored in contemporary physics; ignored not because it has been discredited, but because the field approach of Maxwell's theory is mathematically more appealing and easy to teach. Thus, non-field electrodynamics has been edged out of the university's curriculum. No university today teaches Ampere's law nor the related Weber's electrodynamics.

The purpose of this paper is to show the working of the railgun based on the Ampere's force law. It will be seen that this alternative approach resolves many questions that cannot be easily answered through the traditional approach of the Lorentz force, the most controversial of which is the "seat of recoil". It will be shown that the explanation based on the Ampere's force law is simple and straightforward and nearly all aspects of the working of the railgun fall nicely

Key words and phrases. railgun, railgun recoil, Ampere's force law, Weber's electrodynamics, Ampere's tension, Ampere longitudinal force.

into place without any controversy. A method for integration involving the Ampere force law is given. It then uses it to explain the working of the railgun and to derive some predictions of the characteristics of the railgun operation.

There is a very detailed English translation by Professor A.K.T.Assis of the complete work of Andre-Marie Ampere, with details of the Ampere's force law [3]. Quoting from the book:

> *Hans Christian Ørsted (1777-1851) was a Danish physicist and chemist who worked with the pile. In 1820 he observed the deflection of a magnetic needle from the magnetic meridian when there was a constant electric current flowing in a long wire which was close to the needle. Ørsted's discovery marks the beginning of electromagnetism, that is, of the systematic study of the relation between electric and magnetic phenomena. ... Ørsted did not publish his work in any scientific journal. He wrote it in Latin, with four pages, sending it as a brochure to several scientists on 21 July 1820. It caused a sensation, being translated and published in several scientific journals. Arago (1786-1853) described Ørsted's work to the Academy of Sciences in Paris on 4 September 1820. Due to the generalized disbelief, he repeated this experiment to the members of the Academy on 11 September 1820.*

Ørsted's discovery immediately lead many scientists to investigate this relation between electricity and magnetism. Among the pioneers was Andre-Marie Ampere who, in 1822, proposed his force law between current elements. Hermann Grassmann proposed a competing force law, also between current elements. It was from Grassmann's law that the current Lorentz magnetic force law was derived. Commentators on the two laws have pointed to the "crucial point of controversy" (Cavalleri 1996) in that Ampere's force law obeys Newton's third law, while Grassmann's force law does not. There is one more critical difference between the two competing laws; only Ampere's force law predicts a repulsion between two collinear current elements. This repulsion gives rise to what is now referred to as Ampere tension within a long straight current-carrying conductor. The form of Ampere's law in modern notation is:

$$\mathbf{F_{12}} = -\frac{\mu_0}{4\pi}\frac{I_1 I_2}{r^2}\hat{\mathbf{r}}[2(d\mathbf{l_1}\cdot d\mathbf{l_2}) - 3(d\mathbf{l_1}\cdot\hat{\mathbf{r}})(d\mathbf{l_2}\cdot\hat{\mathbf{r}})] \tag{1}$$

The force is the action of a directed current element $d\mathbf{l_1}$ with current I_1 on a directed current element $d\mathbf{l_2}$ with current I_2; r is the distance between the elements and $\hat{\mathbf{r}}$ is the unit vector from $d\mathbf{l_1}$ to $d\mathbf{l_2}$.

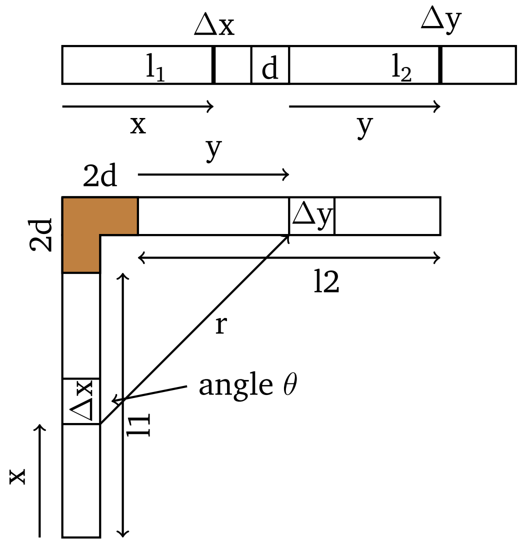

FIGURE 1. Top:Long straight conductor sections l1, l2 separated by small section d. Bottom: Straight conductors at right angle; l1, l2 separated by d/2d.

From the time of Ampere right up till the 1990's, numerous experiments have been performed by various physicists to verify if the controversial Ampere tension does exist [4, 10, 11, 12]. Although controversies still remain today, the evidence supporting Ampere tension seems rather strong. Any evidence of Ampere tension would not be favorable to the Lorentz magnetic force which is based on the Grassmann's law. To examine experiments involving Ampere tension, it would be useful to derive a formula that shows how an electric current would cause tensile stress variations within it.

1.1. **Integration For Collinear Elements.** For two collinear elements dl_1, dl_2, the force is repulsive and is given by: $F = \dfrac{\mu_0}{4\pi}\dfrac{I^2}{r^2}dl_1dl_2$. The following shows the method of integration for the forces between two sections l_1, l_2 separated by a small element d in a long straight conductor as in Fig 1. The integration is to compute the forces between the elements of the sections divided into infinitesimal collinear elements Δx. It seems that such an integration may face a singularity for the force of interaction between two adjacent elements dl_1, dl_2 as $1/r^2$ diverges to infinity. But this singularity does not exist if it is taken that the Δx are all of the same size so that $(dl_1 \times dl_2)/r^2 = (\Delta x \times \Delta x)/(\Delta x)^2 = 1$ as $r = \Delta x$.

The integral required to compute the force between sections l_1 and l_2 is:

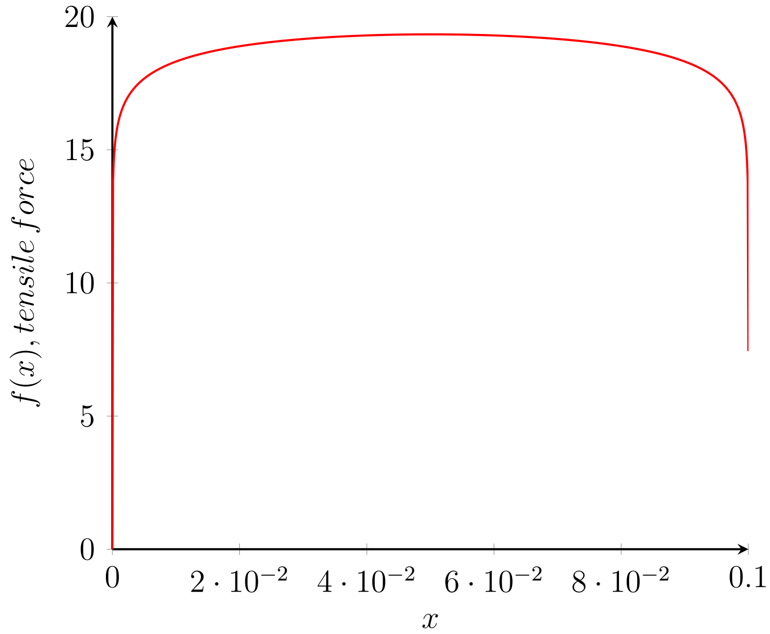

FIGURE 2. Graph showing variation of Ampere tensile force in a long conductor with current I. f(x)=ln(0.1-x)-ln(0.1×1e-10)+ln(x+1e-10). For I=1000A, l=0.1m, d=1x10^{-10}m, the maximum force at the middle is 1.93N.

$$\begin{aligned}
&\int_0^{l_1}\int_0^{l_2} \frac{1}{(y+d+l_1-x)^2}\,dy\,dx = \int_0^{l_1}\Big[\frac{-1}{y+d+l_1-x}\Big]_0^{l_2} dx \\
&= \int_0^{l_1}\Big(\frac{-1}{l_2+d+l_1-x} + \frac{1}{d+l_1-x}\Big)\,dx \\
&= \Big[log(l_2+d+l_1-x) - log(d+l_1-x)\Big]_0^{l_1} \\
&= log(l_2+d) - log(d) - log(l_2+d+l_1) + log(d+l_1);
\end{aligned} \tag{2}$$

Substituting $l = l_1 + l_2 + d$ and eliminating l_2, the integral in equation (2) is : $log(l - l_1) - log(ld) + log(l_1 + d)$.

In practice, the computed force between sections l_1, l_2 for a separation d in the order of one Angstrom (10^{-10}) may be taken to be that between two adjacent sections as one Angstrom is the order of lattice spacing in solid crystals. See Fig 2

1.2. **Integration For Elements In Right Angled Sections.** The method of integration above should also be applicable to compute the forces between two sections l_1, l_2 where they are at a right angle; the angle should be positioned at the center of the element 2d separating l_1, l_2 as in Fig 1. In this case, the relevant term in Ampere's force formula for the interaction between elements $\Delta x, \Delta y$ is only: $3(d\mathbf{l_1} \cdot \hat{\mathbf{r}})(d\mathbf{l_2} \cdot \hat{\mathbf{r}})$; the force is repulsive. The integrand to compute the forces resolved along the x-direction would be: $dl_1 dl_2 cos^2\theta sin\theta / r^2$. As $cos\theta = \frac{l_1 + d - x}{r}$ and $sin\theta = \frac{d+y}{r}$, the integral to be computed is:

$$\begin{aligned}
&\int_0^{l_1}\int_0^{l_2} \frac{(l1+d-x)^2(d+y)}{((l1+d-x)^2+(y+d)^2)^{5/2}}\,dy\,dx \\
&= \int_0^{l_1} \Big[-\frac{(-x+l1+d)^2}{3((y+d)^2+(-x+l1+d)^2)^{3/2}}\Big]_0^{l_2} dx \\
&= \int_0^{l_1} -\frac{(-x+l1+d)^2}{3((l2+d)^2+(-x+l1+d)^2)^{3/2}} + \frac{(-x+l1+d)^2}{3(d^2+(-x+l1+d)^2)^{3/2}}\,dx
\end{aligned} \tag{3}$$

The following is evaluated using the Maxima software:

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integrate((l1+d-x)^ 2*(d+y)/((l1
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$$-\frac{(-x+l1+d)^2}{3\left((y+d)^2+(-x+l1+d)^2\right)^{\frac{3}{2}}} \qquad (\%\ o1)$$

The indefinite integral of equation (3) for the above is too complicated an expression to be useful. The definite integral can easily be evaluated numerically. If we take as an example a railgun with rail length 4m, armature 20cm, d 10^{-10}(1 Angstrom), the integral evaluates to 7.0801. The table below shows the integral for various other lengths. It shows that the integral does not vary much with rail length. This means that a good estimate of the kinetic energy of the armature on exit may be found with just the simple product of the longitudinal component of force on the armature and the rail-length.

```
[l1,l2,d]:[4,0.2,10^ (-10)];

quad_qags(-(-x+l1+d)^ 2/(3*( (l2+d)^ 2+(-x+l1+d)^ 2)^ (3/2))
+ (-x+l1+d)^ 2/ (3*(d^ 2 + (-x+l1+d)^ 2)^ (3/2)), x, 0, 4);
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$$[7.080091380276405\,, 3.1062520855053510^{-8}\,, 1407\,, 0] \qquad (\%\ o2)$$

Integral For Various Rail Length l1					
l1	4m	3m	2m	1m	0.5m
Integral	7.0801	7.0796	7.0782	7.0710	7.0443

We would assume the following parameters for our railgun: armature mass=1kg, l1=4m, l2=20cm, current=300kA. The longitudinal force acting on the armature due to a single main rail, F_r, is given by: $F_r = \frac{\mu_0}{4\pi} \times (300000^2) \times 7.0801 = 63739N$. The total force on the armature would be twice F_r or 127479N. The armature exit kinetic energy would then be: force x distance or 509916J, armature exit velocity 1010m/s(Mach 2.9).

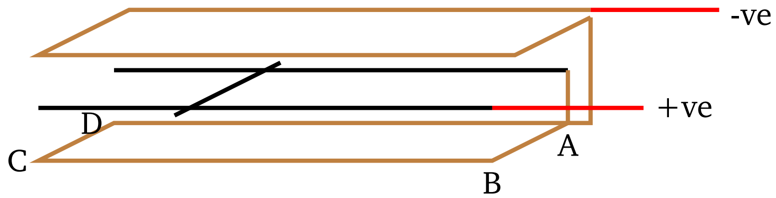

FIGURE 3. Tripled Railgun Design. Main rails black; loop current rails brown.

In addition to the above forces on the rails, there is also the collinear Ampere longitudinal tension. Using the integral from Eq (2), the maximum Ampere tensile force(at the middle) in a 4m long rails is 207293N, about three times that of F_r, the longitudinal recoil force. The Ampere tension seems to vary little for various rail length; the value for rail length 1m is 194812N.

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[l, l1, d, I]:[4, 2, 10^ (-10), 300000];
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$$\left[4\,,2\,,\frac{1}{10000000000}\,,300000\right] \qquad (\%\ o5)$$

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(log(l-l1)-log(l*d)+log(l1+d))*1.257*10^ (-6)/4/%pi*I^ 2,numer;
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$$207292.5107535243 \qquad (\%\ o7)$$

The estimated exit velocity based on the Ampere's force law seems to be in agreement with the expected order of velocity for railguns. This agreement should be supportive evidence for the Ampere's force law.

2. Tripled Railgun Design

As shown earlier, the explanation of the railgun operation based on the Ampere's force law is straightforward; even reliable estimates for the recoil stresses on all the rails could be made. Figure (3) shows the schematic diagram of the tripled railgun. The idea is to have the current doing two loops before it returns to the negative source terminal, once below the rails proper (ABCD) and the other above; the current loops must all be in the same sense. The advantage of this tripled design comes from the fact that the longitudinal force on the armature due to the loop rails(brown) is about twice that by the main rails(black). For the forces between the armature and the loop rail, it is repulsive with the rail section behind the armature and attractive with the section ahead of the armature; the force would therefore be twice of that between the armature and the main rails. With the same operating current, it means that the tripled railgun could increase the armature kinetic energy about fourfold. This is a great design advantage as a targeted power of the railgun may be achieved on a much lower current.

In the following examination of the tripled railgun, the parameters would be assumed to be the same as given earlier. For the tripled-railgun design with the same current, the armature kinetic energy would be 509916x4 or 2039664J giving an exit velocity of 2020m/s(Mach 5.9). Assuming a constant acceleration for the armature, the transit time for armature would be 3.96ms.

In order to estimate the ohmic loss, we assume the material of the rails to be mild steel with resistivity of 10×10^{-8} ohm·m and tensile strength of 400MPa. As the tension within a rail is about 140000N (see below; ampere tension - F_r) and if the rail stress is not to exceed 1/20 of 400MPa, the cross section area of the steel should be about 8cm x 8cm. The total rail length is about 25m giving it a total resistance of 3.9×10^{-4} ohm. The ohmic loss is about 4.6×10^{4}J, just a 2.3% of the armature kinetic energy. From these static analysis (ignoring frictional loss), it seems the railgun should be able to achieve a very high energy efficiency factor. The average railgun operational voltage can be found from: $VIt = armature\_energy$; average operational voltage=1717V.

3. Railgun Recoil

As is well known, there are two electrodynamics theory to explain the working of the railgun; the one based on Maxwell's electromagnetism with the Lorentz magnetic force and the other, the Ampere's force law. It has been shown that the Ampere's force law may be derived from Weber's electrodynamics. Although Weber's electrodynamics is out of favor for almost a century, it has not been discredited. The latter is being supported by the Graneaus' [5] and A.K.T.Assis[3].

As seen from the quoted passages from various sources below, there is much controversy surrounding the *'seat-of-recoil'*. Most authors who favor the Lorentz force argue that there is no recoil at the rails and that the recoil manifests at the breech that closes the circuit electromagnetically. It is explained that the magnetic field carries momentum which, somehow, transmits the recoil forces.

On the other hand, the Graneaus' predicted that the recoil forces manifest in the rails near the armature. They constructed an experiment [5] (1996, page 177) to prove their point. The setup consisted of 40cm of thinner rails made of aluminium or stainless steel; these were pinned to 200cm of thicker copper at the ends. The armature is a fixed copper rod (cannot be ejected) lightly in touch with the thinner rails near the ends. Current pulse of up to 100kA were sent through the copper rails. It was found that the thinner rails experienced buckling. The Graneaus' concluded that: *Only the existence of longitudinal Ampere force can adequately explain the rail buckling.*

There is a critical flaw in this experimental setup to simulate and to verify railgun recoil. A railgun recoil must involve two separate solid body under external action-reaction forces. The railgun recoil is a reaction to external forces acting on the rails. In the above setup, there is only one single solid body; the armature may be taken to be an extension of the solid body of the railgun proper. Any forces of interaction in the setup are internal forces only and such forces are irrelevant in order to determine the seat-of-recoil in railguns. It seems this experiment cannot be accepted.

The following are some quoted passages from other sources in favor of the recoil being only at the breech and not on the rails:

> *Recoil forces in EM railguns appear wherever the breech of the railgun is closed electromagnetically. This means recoil forces may appear on* ***power supply leads, switches, or power supply components themselves.*** [9]

The authors of the above go into some length to discuss designs to avoid recoil acting on the power source.

> *An experiment has been developed that allows for the simultaneous measurements of the quasi-static Lorentz force on the armature and rail recoil. ...Force measurements show that the force on the armature increases as the square of the current while the indicated reaction force on the rails is an artifact of the experiment. These recoil forces measured <1% of the force on the armature.* ***We conclude that the recoil ...is not seated in the rails.*** [8]

An interesting report from: US Army Armament Research, Development And Engineering Center. Technical Report ARCCB-TR-00016:

> *WHERE IS THE RECOIL FORCE MANIFEST DURING LAUNCH?* [7] *A common area of confusion and discussion regarding recoil of railguns centers around two schools of thought on just where the reaction force of launch is applied to the cannon. One school of thought argues that the recoil force is exerted at the breech of the railgun (ref 3). The other, most notably championed by P. Graneau, argues that the recoil forces are manifest along the rails near the armature (ref 4). Those wishing to resolve the apparent paradox of railgun recoil for themselves need only consult a basic textbook in fundamental physics ("The Feynman Lectures on Physics",volume two, section 27) to learn that electromagnetic fields themselves carry momentum. This fact is required for the simple application of the Biot-Savart law to two charged particles traveling through space in order for their reactions to satisfy Newton's third law: conservation of*

> *momentum. The allure of Graneau to unwitting engineers is that he provides a comfortable means to visualize continuity of momentum within the single-turn, current loop of a simple railgun. Mathematicians (ref 8) and experimentalists (ref 9) have demonstrated that under complete integration of the current loop, the reaction occurs at the breech. However, this provides little solace to those uncomfortable with the concept of rails near the armature pushing it while the reaction is to occur at the breech, which is a direct consequence of an element-by-element interpretation of the Biot-Savart law. Consulting Feynman et al. (ref 6), who elegantly provide comfort that momentum must be locally conserved, may restore solace. Therefore, it is the fields that communicate the momentum from the armature to the breech. Misunderstanding of the field momentum by engineers has been attributed to an unfortunate means of undergraduate instruction based on "action at a distance" with calls for revising the pedagogical approach (ref 10).* ***The bottom line, recoil momentum for a railgun is manifest at the breech.*** *...*

The author takes issue with the above statement: "*This fact (that electromagnetic fields themselves carry momentum) is required for the simple application of the Biot-Savart law to two charged particles traveling through space in order for their reactions to satisfy Newton's third law: conservation of momentum.*". Kathe assumes that two moving charged particles traveling in space would experience the Lorentz magnetic force. This is only a theoretical assumption, not an experimental fact. The author has papers that show that the concept of the magnetic field has inconsistencies that render the Biot-Savart law - thus also the Lorentz magnetic force law - to be invalid [1, 2]. It is doubtful if it can be experimentally verified that a moving electric charge in space would produce a magnetic field as given by the current form of the Biot-Savart law.

Baoming Li. The National Key Laboratory of Transient Physics, Nanjing University of Science and Technology:

> *Abstract:Moreover, large amount of longitudinal force was transmitted to the breech by the electromagnetic field in the form of surface force. The exact position and distribution of recoil were related to the current input device. ... In the previous studies of other researchers, it is always controversial to use Ampere or Lorentz force to calculate the longitudinal force on the rails. Graneau.P insisted that Ampere force should be utilized to calculate the longitudinal forces on the rails. Calculations*

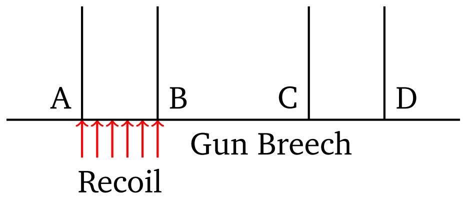

FIGURE 4. Seat of recoil at interfaces AB,CD separating the atoms of the rails and those at the gun breech.

> *results indicated that the force acts near the armature. This phenomenon has also been found by experiments. ... The reverse longitudinal force is mainly concentrated on the field around the breech. Different current input structures produce different electromagnetic field distribution at the breech, which also leads to inconsistent distribution of recoil.* ***However, it is certain that the main recoil does not act on the rails.*** [6].

3.1. **Recoil Based On Ampere's force Law.** The author has no details on the method of calculations that the Graneaus' used to conclude that the gun recoil acts on the rails. If the method of integration of the Ampere's forces as presented earlier is without issue, then there is no recoil on the rails; a better descriptive would be, *there is no recoil manifests on the rails*.

The mechanics for all gun recoil is the same. The firing of a gun always involve activating a repulsion between two solid bodies, the projectile and the gun. In the case of cannons using chemical propellants, the deflagration of the propellant produces a highly heated gas mixture that pushes the projectile forward. The recoil would be at the base of the cannon barrel, i.e. the breech. There is no longitudinal force acting on the length of the barrel; an expressive description could be *'there is no recoil manifests on the barrel'*. Now, if someone were to use a sledgehammer to give a heavy blow to the muzzle of the cannon, then again there is recoil from the heavy blow; but in this case the barrel as well as the cannon breech all take the same compressive stress from the blow. Here, we may say *'the recoil is also manifest on the barrel'*.

In the case of the railgun the two separate solid bodies are the armature and the railgun proper; the railgun proper being the rails firmly fixed to the gun breech. The sole purpose of the breech is to take the recoil when the railgun is fired. Without the breech, firing the railgun means firing the armature in one way and firing the rails the other way! This is not what the railgun is designed for.

Using the earlier calculated values for our 4m tripled railgun, the longitudinal repulsive force between a single main rail and the armature is F_r = 63739N. During the railgun firing, an external force of F_r acts on the rails; it is compressive in nature. But within the rail, there is also the Ampere tension (collinear) of 207293N, an internal force within the rails. The net action is that the rails experience a net tensile force when the railgun is fired - not compressive; the value is 207293N - 63739N = 143554N. This may seem contradictory as some part of the gun must provide the recoil to the armature. As will be explained below, there is no contradiction; it is just the way the Ampere's force law works. The schematic for the actual recoil is shown in Fig (4).

It has been explained earlier that the repulsive force between a single coil rail and the armature is about twice F_r. But for the coil rails, there is an additional tensile force due to the repulsion between the transverse section with the longitudinal sections, as between CB and CD in Fig (3); this tensile force also has the value F_r, but is absent in the main rails. Overall for the coil rails, the net action is a tensile force of 207293N + 63739N - 2x63739N = 143554N, the same tensile force as would occur in the the main rails.

For our tripled railgun, our calculations have shown that the average longitudinal force acting on the armature during firing would be about 4 x (2 x F_r) or 509912N. This would mean that the armature would exert this same force component on the railgun proper, i.e. the rails fixed to the gun breech. This force of 509912N is an external force which would elicit a reaction from the railgun proper. In other words, the recoil force of 509912N has to be absorbed in order to prevent the railgun from moving backwards.

What we have is that during the railgun firing, the external forces acting on the railgun proper are through the rails only; the Ampere force law does not provide for any action of the armature directly on the gun breech. The only conclusion is that this external forces are transmitted through the rails and act on the gun breech. To be precise, the seat of recoil is the *'empty space'* in the interfaces separating the atoms of the rails and the breech as in Fig(4).

> *The seat of recoil is precisely at the* 'empty space' *in the interfaces separating the atoms of the rails and the atoms of the breech*;

This recoil force is completely absorbed by the inter-molecular forces preventing the merging of the solid matter of the rails with the solid matter of the breech. Based on the Ampere force law as the explanation of the working of the railgun, it is correct to say there is no recoil manifest on the rails.

4. Conclusion

This paper has used analytic integration of the Ampere forces to explain the operation of the railgun. Estimations on the operational characteristics is done on a typical tripled railgun design with rail-length 4m made of mild steel, cross-section 8cm x 8cm, armature width 20cm, armature mass 1kg and average operating current of 300kA. An exit velocity of 2020m/s (Mach 5.9) may be reached with kinetic energy 2.04MJ. It is found that the ohmic loss is small, just about 3% of the armature kinetic energy. This would mean that the tripled railgun design should be able to achieve a high energy input to kinetic energy efficiency. When analyzed based on the Lorentz magnetic force, the seat of recoil for the railgun cannot be precisely located. On the other hand, based on the Ampere force law, the seat of recoil has been determined precisely; it is at the *'empty space'* in the interface separating the atoms of the rails and the atoms of the gun breech. During firing, contrary to expectation, the rails would be under tension and not compression.

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