THREE-DIMENSIONAL RAIL-CURRENT DISTRIBUTION NEAR THE
ARMATURE OF SIMPLE, SQUARE-BORE, TWO-RAIL RAILGUNS

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Abstract: Vector potential is solved as a three dimensional, boundary value problem for a conductor geometry consisting of square-bore railgun rails and a stationary armature. Conductors are infinitely conducting and perfect contact is assumed between rails and the armature. From the vector potential solution, surface current distribution is inferred.

Introduction

Various methods have been previously developed for calculating rail current distribution by approximating rails as having infinite conductivity.[1,2] These calculations involve regions of rail behind and remote from armatures. Richard Marshall presented a qualitative discussion concerning surface current distribution on regions of rail near armatures.[3]

As a sequel to Marshall's qualitative discussion, this paper uses magnetic vector potential solutions to gain additional insights concerning current distribution on armatures and on regions of rail close to an armature. This paper treats rail-armature configurations with rectangular cross-sections which are of equal height and are approximated as infinitely conducting. The armatures are considered to be locked in place and bridge the gap between long rails, so that the armatures and rails form an "H." Additionally, perfect contact between armature and rails is assumed, so the "H" is treated as one continuous conductor. Rail supporting structures are ignored and the rail-armature conductor system is assumed to exist in free space. Figure 1 depicts the geometry and defines some terms used throughout the paper.

Preliminary Considerations

Before solving for the magnetic vector potential in infinitely conducting rails and armature, it is useful to qualitatively consider general features of the solution and review known facts concerning rail current distribution. In regions of infinitely conducting rails remote from and behind an armature, rail current resides on rail surfaces and flows longitudinally along the rails, parallel to the railgun bore. Here, the magnetic vector potential, $\bar{A}$, obeys a two-dimensional Laplace equation as discussed by Kerrisk.[1] This can be seen by starting with Ampere's Law in the magnetostatic case,

$$\nabla \times \bar{B} = \mu_0 \bar{J} \quad (1)$$

where $\bar{B}$ is magnetic flux density and $\bar{J}$ is current density. Defining the magnetic vector potential in the usual manner, by the equation $\bar{B} = \nabla \times \bar{A}$; using the vector identity $\nabla \times (\nabla \times \bar{A}) = \nabla (\nabla \cdot \bar{A}) - \nabla^2 \bar{A}$; and setting the divergence of $\bar{A}$ to be zero (see equations 7 through 9 for more discussion on this requirement), yields the following equation relating the vector potential and current density:

$$\nabla^2 \bar{A} = -\mu_0 \bar{J} \quad (2)$$

Figure 1. (a) Top view of rail-armature conductor system, connected to a power source. Assuming perfect rail-armature contact, the conductors form a single continuous conductor. Some rail and armature surfaces, perpendicular to the plane of the page, are named to remove ambiguity in the remainder of the paper. (b) Top view of right half of armature and part of right rail. Dashed line represents interior surfaces which marry with the remaining rail and armature conductors to form diagram (a). For this paper, "interior" is used to designate those portions of conductor not in contact with free space

For long, parallel conductors, as in railguns in a region remote from the armature, current is entirely in one direction which can be defined to be in the y direction. Then, in Cartesian coordinates,

$$\bar{A} = A_{y,r} \bar{j} \quad (3)$$

and equation 2 becomes the two-dimensional scalar equation:

$$\nabla^2 A_{y,r} = \mu_0 J_{y,r} \quad (4)$$

where the y subscript denotes the Cartesian component and r indicates a region of rail remote from and behind the armature. On the rail interior, i.e., portions of rail not in contact with free space, $J_{y,r}$ is zero and equation 4 becomes the Laplace equation. Boundary conditions require the vector potential to be continuous at rail surfaces [4]. Since $\bar{B}=0$ on the rail interior, the equation $\bar{B} = \nabla \times \bar{A}$ applied to this two-dimensional situation yields the result that $A_{y,r}$ is constant everywhere on the rail interior and on rail exterior surfaces (remote from and behind the armature). Additionally, considering

symmetry and the direction of current flow on the two rails, it is apparent that the vector potential is equal in magnitude and opposite in direction for the two rails. If armature position is near the muzzle, rails behind the armature can be considered as long parallel conductors. In this case, end effects have little influence on current distribution over most of the rails remote from and behind the armature. The situation for this region of rails is analogous to an electrostatic problem concerning a capacitor consisting of two long, rectangular conductors held at equal but opposite electric potentials. The properties and solutions for the y component of the magnetic vector potential and the electric scalar potential are identical, as are the resulting surface current and surface charge distributions. Various numerical techniques for calculating the surface current distribution on this portion of long (infinitely conducting) rails have been developed [1,2] and typical results are presented in figure 2.

Figure 2. Normalized surface-current density for the upper half of the right rail of an infinitely-conducting, two-rail, square-bore railgun on a portion of rail remote from the armature. Rail height = 4.0 cm. Rail thickness = 1.0 cm. Bore = 4.0 cm. The position axis originates at the center of the inside surface of rail, proceeds around the top of the rail and ends at the center of the backside of the rail (external to the bore). The two peaks correspond to rail corners. The corners had a 1.0 mm radius for this computation

At the center plane of infinitely conducting armatures, midway between the rails (face #2 in figure 3), current distribution is not known. However, on this armature midplane, symmetry dictates that the current and magnetic vector potential consist of only negative J_x and A_x components, respectively. Therefore, at the armature midplane,

$$\bar{A} = -A_{x,m} \bar{i} \quad (5)$$

where the x subscript denotes the Cartesian component and m indicates armature midplane. Again, equation 2 becomes a two-dimensional Poisson equation:

$$\nabla^2 A_{x,m} = \mu_0 J_{x,m} \quad (6)$$

Since conductivity is infinite, armature interior current is zero and equation 6 becomes the Laplace equation. Again, $A_{x,m}$ is constant everywhere inside and on the armature surface (at the armature midplane).

The task, now, is to find a magnetostatic solution for the magnetic vector potential inside the infinitely-conducting rails and (stationary) armature with the following properties:

1. in rails, remote from and behind the armature, $\bar{A} = \pm A_{y,r} \bar{j}$, where $A_{y,r}$ is a constant and the $\pm$ sign refers to the fact that $\bar{A}$ is oppositely directed in the two rails
2. in the armature, at the midplane, $\bar{A} = -A_{x,m} \bar{i}$, where $A_{x,m}$ is a constant.

The generality of the solution can be addressed by examining uniqueness properties. Then, from the magnetic vector potential solution, properties of the current distribution can be inferred.

Problem Formulation and Uniqueness Properties

This section develops equations which govern the magnetic vector potential on conductor interiors (for $\sigma = \infty$) and discusses uniqueness properties for the problem being addressed in this paper. A vector potential solution is developed in the next section.

Using the definition for the magnetic vector potential:

$$\nabla \times \bar{A} = \bar{B} \quad (7)$$

it can be shown that $\bar{A}$ obeys the following equation [5]:

$$\bar{A}(\bar{r}) = \frac{\mu_0}{4\pi} \int_{\Omega} \frac{\bar{J}(\bar{r}')}{|\bar{r} - \bar{r}'|} dV' + \nabla f(\bar{r}) \quad (8)$$

In equation 8, the integration is over a region of space which includes all current sources, and $f(\bar{r})$ is any scalar function. It is necessary to specify $f(\bar{r})$ in order to proceed. Since the divergence of the integral term in equation 8 is zero, it is advantageous to select $f(\bar{r})$ equal to zero. Then the following equation results, which is known as the Coulomb gauge:

$$\nabla \cdot \bar{A} = 0 \quad (9)$$

Note that, with $f(\bar{r})=0$, equation 8 indicates that infinitely far from source currents, the vector potential is zero.

With equations 7 and 9 to define $\bar{A}$, interface conditions between two media need to be addressed. These are derived by Shadowitz [5, pg 334] and for completeness the derivations are summarized here. Since equation 9 holds everywhere, even on the interface boundary, integrating equation 9 over a differential pill box based partly in each of the two media, yields $A_{1n} - A_{2n} = 0$. Since $\bar{B}$ stays finite everywhere, even in the presence of surface currents, integrating equation 7 over a differential rectangle based partly in each media yields $A_{1t} - A_{2t} = 0$. Therefore, the conditions at the interface between any two media are:

$$A_{1n} = A_{2n} \quad (10)$$

$$A_{1t} = A_{2t}$$

where the n and t subscripts refer to normal and tangential components, respectively. Note that these conditions apply even in the presence of surface currents.

An additional restriction concerning the normal component of $\bar{A}$ at the interface between conducting and nonconducting media is applicable. Assuming no local charge build-up, $\nabla \cdot \bar{J} = 0$ everywhere in space and, more specifically, it also independently applies to isolated regions of space occupied by continuous conductors. As a result, the normal component of $\bar{J}$ is zero at conductor surfaces; the same requirement can be conveniently imposed on $\bar{A}$. This requirement on $\bar{A}$ enforces equation 9 on a local basis, in the same regions of space for which $\nabla \cdot \bar{J} = 0$. Considering equation 8, with $f(r)=0$, enforcing $\nabla \cdot \bar{A} = 0$ individually within each conductor automatically causes $\nabla \cdot \bar{J} = 0$ to be satisfied within each conductor. Enforcing equation 9 on a local basis is common in finite element programs for electromagnetic problems [6].

Finally, it is noted that on the interior of infinite conductivity conductors, the magnetic field is zero. To summarize, the equations governing the magnetic vector potential inside infinitely conducting rails and armature and the equations concerning the interface conditions at conductor surfaces are:

$$\begin{aligned}\nabla \cdot \bar{A} &= 0 \\ \nabla \times \bar{A} &= \bar{0} \\ A_{1n} &= A_{2n} = 0 \\ A_{1t} &= A_{2t}\end{aligned}\quad (11)$$

With equations 11, the vector potential, $\bar{A}$, associated with the infinite conductivity rails and armature can be treated as a boundary value problem. As discussed by Shadowitz [5], for this magnetostatics problem in the Coulomb gauge, a given magnetic field, $\bar{B}$, yields a unique vector potential, $\bar{A}$. Shadowitz further indicates that there is a unique distribution of current over the rails which produces this vector potential. Proof of the general property that specifying the divergence and curl of a vector guarantees a unique solution, to within a constant, is provided by Borisenko and Tarapov [7]. Fixing $f(r)$ as zero in equation 8 removes the ambiguity of the constant.

Vector Potential Solution

With uniqueness guaranteed, it remains to find a solution for the vector potential which describes magnetic field and current conditions associated with the infinitely conducting rails and armature. This solution is readily obtained by considering a more familiar analogous problem. The analogous problem concerns a *finite* conductivity conductor system with the same geometric shape as the rails and armature shown in figure 1. The problem is to determine the electric field, $\bar{E}$, which would exist if a steady state, direct current (dc), fully diffused current were flowing through the rails and stationary armature. Assuming no build-up of static charge, this analogous problem is governed by the following equations:

$$\nabla \cdot \bar{E}_{dc} = 0 \quad (12)$$

$$\nabla \times \bar{E}_{dc} = 0 \quad (13)$$

$$E_{1n} = E_{2n} = 0 \quad (14)$$

$$E_{1t} = E_{2t} \quad (15)$$

$$\bar{J}_{dc} = \sigma \bar{E}_{dc} \quad (16)$$

where the dc subscript is meant to emphasize that this is a steady state, dc, fully-diffused current problem. Equations 12 through 15 are identical in format to equations 11 which govern the magnetic vector potential.

Steady state, dc electric field problems are readily solved using electric scalar potentials, which have well known boundary and interface conditions. It is only necessary to consider the portion of the rail-armature system shown in figure 3. This system consists of half the armature and a portion of the right rail. The near face of the rail, designated as face #1 in figure 3, is remote from the armature. Here the dc electric field (and the dc current) is uni-directional, parallel to the rail surfaces, in the y direction, and has a constant magnitude. This can be obtained using the same techniques used to prove $A_{y,r}$ constant (see equation 3). Similarly, by symmetry, at armature midplane (designated as face #2 in figure 3), the dc electric field is parallel to the armature surfaces in the negative x direction and has constant magnitude. This is obtained using the same techniques used to prove $A_{x,m}$ constant (see equation 5). It is apparent that the electric potential which corresponds to this situation, Φ_{dc} , has one constant positive value assigned everywhere on face #1 and a lesser constant positive value assigned everywhere on face #2. Neumann boundary conditions, $\partial \Phi_{dc} / \partial n = 0$, are imposed on all other conductor surfaces, in accordance with equation 14. By equations 12 and 13, Φ_{dc} obeys the following equations in the armature and rails:

$$\bar{E}_{dc} = -\nabla \Phi_{dc} \quad (17)$$

$$\nabla^2 \Phi_{dc} = 0 \quad (18)$$

Note, there is an imposed electric potential difference between face #1 and face #2 in figure 3, which creates potential gradients in the x and y directions. However, due to symmetry and the lack of imposed electric potential differences between the top and bottom surfaces (face #3 and face #4 in figure 3), $\partial \Phi_{dc} / \partial z = 0$. Therefore, the z component of $\bar{E}_{dc}$ is zero, and there is no dc current flow in the z direction, i.e., the z component of $\bar{E}_{dc}$ and $\bar{J}_{dc}$ are zero everywhere. This result agrees with intuition for the dc, finite conductivity, fully-diffused, steady state problem addressed here (recall that rails and armature have the same height and same rectangular cross-sections). Therefore, the problem reduces to two dimensions, with all conductor slices parallel to the x-y plane having identical solutions for $\bar{E}_{dc}$. For the geometry here, a two-dimensional numerical solution for Φ_{dc} and $\bar{E}_{dc}$, using finite differences or finite elements, is easily obtained. As previously mentioned, since divergence and curl are both specified for $\bar{E}_{dc}$, the solution (for these boundary conditions) is unique.

Figure 3. Three-dimensional view of right half of the armature and part of right rail. This picture corresponds to figure 1 (b). Face #1 and face #2 are interior faces which marry with the remainder of the right rail and the left half of the armature, respectively, to form the complete "H" of figure 1 (a). All other faces, even those hidden from view, are surfaces which interface with free space

The solution techniques discussed in the previous paragraph for the finite conductivity, dc, steady state, fully-diffused current situation to find $\vec{E}_{dc}$, apply equally well to determining the magnetic vector potential, $\vec{A}$, for infinitely-conducting rails and armature. Note that, by equations 11 through 15, $\vec{E}_{dc}$ and $\vec{A}$ obey identical equations and have identical conditions at external conductor surfaces. Further, note that $\vec{E}_{dc}$ and $\vec{A}$ at armature midplane both have constant magnitudes and both are directed in the negative x direction. In regions of rail remote from and behind the armature, both fields have constant magnitudes and are in the y direction. Therefore, except for a multiplicative constant, $\vec{E}_{dc}$ (for finite conductivity) and $\vec{A}$ (for infinite conductivity) have identical solutions.

A solution for the vector potential associated with infinite conductivity rails and armature can now be presented. As for $\vec{E}_{dc}$, there is no z component for $\vec{A}$. Therefore, it is only necessary to present a two-dimensional solution for $\vec{A}$ in an x-y plane. To obtain the solution, Laplace's equation for a magnetic scalar potential function in two dimensions, for an x-y cross-section of the rail-armature conductor system, was numerically solved using finite difference methods. The potential over face #1 of figure 2 was set to a constant positive value, and the potential over face #2 was set to a lesser constant positive value. Normal derivatives of the scalar potential were fixed at zero over all exterior conductor surfaces. The vector potential, $\vec{A}$, was obtained from the gradient of the scalar potential solution. Figure 4 presents a plot of four vector potential field lines, in the x-y plane, for a rail-armature conductor system. The field lines were selected to provide a picture of magnetic vector potential direction. There was no attempt to ensure that field line spacing exactly corresponds to vector potential magnitude. To do so, would require equal line spacing at regions of rail remote from the armature and at the armature

Figure 4. Plot of four vector potential field lines for an x-y cross-section of the infinitely-conducting rails and armature. Solid lines delineate boundaries of rail and armature. Field lines are depicted by the dotted lines. Additional vector potential field lines are coincident with conductor boundaries.

midplane. Since one field line traces the conductor perimeter (recall $A_n = 0$) equal spacing would preclude plotting field lines which are close to conductor edges, as was done in figure 4, unless a large number of field lines were plotted. Nevertheless, it is apparent from figure 4 that the vector potential has a very small magnitude in the region of rail ahead of the armature. Any x-y slice of conductor has an identical solution for $\vec{A}$.

Distribution of Surface Current

From the vector potential solution, certain facts concerning surface current over armatures and nearby portions rails can be inferred. First, the fact that the z component for $\vec{A}$ is zero, in conjunction with equation 8 with $f(\vec{r})=0$, implies that there is no z component to surface current. This means that current on rail backsides (positions greater than 3 in figure 2) does not flow up and over the top of rails, but flows the full length of the rails and around rail-ends to reach the armature. Although this may seem unlikely at first, it does agree with likely pictures of the magnetic field, $\vec{B}$, in and around railgun bores.

Figure 5 depicts the approximate paths of some likely magnetic field lines for a rail-armature conductor system. Field line #1 is somewhat remote from the armature. It originates behind the armature, circles the right rail and closes on itself in the bore. This is consistent with the fact that current on this portion of rails is entirely in the y direction and is distributed over all four rail surfaces. Field line #2 originates close to the armature, toward the center of the bore. It circles the armature and closes on itself in the bore. This is consistent with current existing on all four exterior armature surfaces, including the front (facing the muzzle of the railgun). Field line #3 follows a path similar to Field line #2. Field line #3, however, passes close to the inside surface of rails in front of the armature, and is consistent with current in front of the armature, on rail inner surfaces, directed toward the armature. Field line #4 originates in the bore close to the armature and close to the rail, near the corner formed by the inside rail surface behind the armature, and the back armature surface. To close on itself, this

Figure 5. Three-dimensional sketch depicting a few probable magnetic field lines. A segment of right rail and the right half of an armature are shown

field line curves partly over the armature and to the right of the right rail, in front of the armature. This is consistent with current in front of the armature, on rail backside surfaces, proceeding toward the muzzle end of the rail.

It should be mentioned that equation 8 by itself, with $f(r)=0$ and $A_z=0$, only indicates that the integral of the z component of current is zero. However, current distribution for the top and bottom halves of rails are identical. Therefore, applying equation 8 to a point on a rail off the one x - y plane that bisects the rail-armature conductor system, leads to the conclusion that J_z equals zero everywhere.

If the armature is close enough to the muzzle, trailing rails can be considered as long. For this case, surface current distribution on front and back armature surfaces, and inside and backside rail surfaces is known. This distribution is now known both remote from and close to the armature. Since there is no z component to current anywhere, the distribution on inside and backside rail surfaces which exists remote from and behind the armature, prevails on all conductor planes perpendicular to the x - y plane. This distribution can be calculated, and corresponds to the portions of figure 2 with positions less than 2 for rail inside surfaces, and greater than 3 for backside surfaces. The only remaining unknown is the surface-current distribution on rail top and bottom surfaces (face #3 and face #4 in figure 3). This distribution will now be addressed.

The distribution of surface current on rail top surfaces remote from the armature is known. Here, current is in the y direction and distributed in accordance with figure 2 for positions between 2 and 3. If the direction of $\vec{J}$ were known everywhere, it would be possible to combine this directional information with the distribution information contained in figure 2 to develop a field plot of $\vec{J}$ everywhere on rail top surfaces. Equation 8 provides a first approximation to the direction of $\vec{J}$ on top rail surfaces. The denominator term in the integral implies that the largest contribution to $\vec{A}$ at any particular point comes from nearby currents. This implies that $\vec{J}$ and $\vec{A}$ have roughly identical directions at most points. More precise directional information

can be determined from equations 1 and 7 which are two curl relations involving $\vec{B}$ and $\vec{J}$ and $\vec{B}$ and $\vec{A}$, respectively. Since $\vec{J}$, $\vec{A}$, and $\vec{B}$ all have zero normal components at conductor surfaces, they are coplanar (at conductor surfaces). The following discussion will use

the curl relations to show that both $\vec{J}$ and $\vec{A}$ are perpendicular to $\vec{B}$ on conductor surfaces, and therefore parallel to each other. Since $\vec{A}$ is known on and inside conductor surfaces (figure 4), the direction of $\vec{J}$ on all conductor surfaces, including face #3 and face #4 in figure 3, will then also be known.

The integral form of equation 1 relates a closed line integral of $\vec{B}$ to the flux of current through the surface enclosed by the integration path, c , as follows:

$$\oint_c \vec{B} \cdot d\vec{l} = \mu_0 \int \vec{J} \cdot d\vec{a} \quad (19)$$

Consider a region of space which includes a portion of conductor surface small enough that $\vec{B}$ can be taken as constant on the conductor surface. Of course, $\vec{B}$ is zero inside the surface. Assign a local coordinate system such that $\vec{B} = B_x \hat{i}$ and the x - y plane coincides with the conductor surface (see figure 6). Then, an integration path for equation 19 in the y - z plane is zero, since B_y and B_z are zero. This indicates that $J_x = 0$. Integration in the x - y plane is zero because B_y is zero and B_x is constant over this small region of space. This infers that $J_z = 0$, which was known since $J_n = 0$. Integration in the x - z plane, with one part of the path immediately above the conductor and one part below the conductor, yields a nonzero result. Therefore, the only nonzero component of current is J_y and $\vec{J}$ is perpendicular to $\vec{B}$. Of course, these conclusions are only valid to the extent that $\vec{B}$ becomes constant for a vanishingly small region of space, a common approximation. In fact, this approximation is used when deriving the standard, well known interface conditions on electric and magnetic field tangential components [8].

Similar to the previous paragraph, equation 7 yields the following integral equation:

$$\oint_c \vec{A} \cdot d\vec{l} = \mu_0 \int \vec{B} \cdot d\vec{a} \quad (20)$$

Although the fact that $\vec{A}$ is not necessarily zero inside conductors complicates analysis somewhat, techniques of the previous paragraph can be applied. Consider the same conditions, coordinate system, and integration paths of the previous paragraph. For the y - z integration, the right-hand side of equation 20 is nonzero. Since the normal component of $\vec{A}$ is zero, A_y is nonzero.¹ Now consider an x - z integration path. Here the right hand side of equation 20 is zero. This implies either that A_x is

¹Although not related to the direction of $\vec{A}$, it is interesting to note that this also implies that A_y above the conductor surface is not equal to A_y below the surface (i.e., $\partial A_y / \partial z \neq 0$). However, equation 10 specifies that as the path gets thinner, i.e., upper and lower paths become very nearly coincident with the conductor surface, A_y above and A_y below become equal. This agrees with the fact that the magnetic flux for this integration then approaches zero.

Figure 6. Local coordinate system and three paths of integration

zero or that A_x is a nonzero constant in this region of this x-z plane. In both cases, $\partial A_x / \partial z = 0$. Note that this region includes portions of space external to conductor surfaces. Equation 8, with $f(r) = 0$ so the vector potential vanishes at infinity, implies a variation such that A_x is not a nonzero constant over this region of x-z plane. Thus, $A_x = 0$. The last integration, in the x-y plane, corresponds to a zero right hand side to equation 20 and provides no new directional information. This concludes the discussion based on two similar curl relations, which shows that $\vec{J}$ and $\vec{A}$ are parallel on conductor surfaces.

Current distribution for the infinite conductivity rails and armatures, assuming no motion, can now be summarized as follows:

1. Remote from and behind armatures, $\vec{J} = J_y \hat{y}$. The magnitude of J_y varies as depicted in figure 2.
2. For rail and armature surfaces perpendicular to the x-y plane, the distribution of figure 2 for positions less than 2 and greater than 3, prevails, unchanged.
3. For the rail and armature top and bottom surfaces (face #3 and face #4 of figure 3), current distribution remote from and behind the armature is in accordance with figure 2 for positions between 2 and 3. Additionally, individual current "field" lines at all points on these conductor surfaces are parallel to vector potential field lines, which are depicted in figure 4.

4. References to figure 2 in items 1 through 3, above, assume the armature is close to the muzzle and rail conductors behind the armature can be approximated as long. Otherwise, a different (unknown) distribution replaces figure 2 in the aforementioned observations.

Conclusion

In conclusion, a solution for the magnetostatic vector potential inside square bore railgun geometries has been obtained. This yielded considerable insight concerning railgun surface current distribution near armatures.

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