A Solution to Inhomogeneous 3D Railgun

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ABSTRACT: In railgun, which is used to accelerate objects, electrical energy is used to drive the system. In order to reach hypervelocity, a power supply with immense amount of energy must be used which causes an extra ordinary current on the rail and the armature. This current makes thermal energy by ohmic attenuation and warms up various points and therefore changes the electrical, thermal and mechanical specifications of the structure. This paper present a method by which one can consider the inhomogenity created by temperature changes along the structure. In this method, the instantaneous current distribution in the structure and the heat caused by it are calculated, and then the temperature distribution is obtained. The electrical conductivity (σ), thermal conductivity (k) and specific-heat (c) are considered inhomogeneous and are calculated at every instant until the specifications of the material forming the structure be corrected at any instant. Three dimensional finite element method with non-uniform meshing at any instant is used.

1. INTRODUCTION

The railgun is an equipment which is used to launch a projectile using electromagnetic forces. It is used in the fields of weapons, nuclear physics, launching of objects to space and etc. This equipment is really a Direct Current Linear Motor (DCLM), which its armature can move on the length of the stator and gets out of it. Figure (1) shows a simple structure of the Railgun. The armature's force is calculated from the following relationship:

$$\vec{F} = \iiint \vec{J} \times \vec{B} \, dv \tag{1}$$

where J is the current density on the armature and B is the magnetic flux density.

The vast amount of current which passes through the rail and the armature causes them to warm up. This increase in the temperature changes electrical and thermal specifications of the constituent parts and makes the structure an inhomogeneous media. Without considering this matter, the electrical quantities (current and field distribution) and mechanical quantities (distribution of force and velocity) were reported for homogeneous structure [1]. Also the temperature distribution due to ohmic attenuation caused by current flowing from such a system is being considered [2]. In this article by considering inhomogeneity of electrical and thermal specifications of the materials forming the structure, the quantities of current, field, temperature, force and velocity are calculated more accurately.

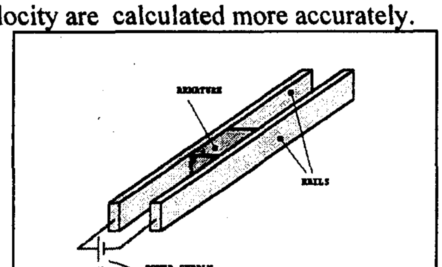

fig 1) simple structure of the railgun

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2. METHOD AND STAGES OF THE SOLUTION

For solving the railgun problem, the following stages of solution in any time steps of the armature's motion is being done and in each stage the obtained quantities are being considered as the initial condition for the next stage.

2.1. MESHWORK

Considering the existing symmetry in Fig.(1), it is sufficient to solve only one half of the railgun's structure. The voltage of the structure is +Vo volts on the top rail and -Vo on the bottom rail . In the solution for half of the structure, the voltage on the structure's symmetry plane which is in the middle of the armature will be zero and -Vo will be acted upon the bottom rail. In our indicated model Vo is set equal to 1250 volts.

As the dimensions of the mesh have inverse relation with the accuracy of the answers, therefore, to increase the accuracy small meshes are used. This act increases the number of elements and consequently increases the needed computer's memory and time. In some cases , the existing memory may not be adequate to solve the problem . The best way to create equilibrium between accuracy in the solution and proper number of elements, is to use nonuniform meshes. Therefore bigger elements are used in parts of the problem where quantitative changes are the function of the predicted answer and smaller elements are used in the more sensitive parts. The above meshwork is shown in the figures related to the distribution of the field and current.

On the other hand, in the finite elements method the nodes located at the boundary of the rail and armature should retain their continuity. Not only the dimensions of the elements along the boundary of the rail-armature must be the same, but also the time intervals between successive solutions with respect to the instantaneous velocity of the armature must be obtained such that it doesn't disturb the continuity of the nodes. Our model which consists of a copper rail with dimensions of 100*2*1 cm and an aluminum armature with dimensions of 5*1*1 cm is discreted to 2016 brick elements with 3372 nodes.

2 .2. ELECTRICAL ANALYSIS

The goal of electrical analysis is to solve the following equation with the conditions mentioned in the previous section:

$$\nabla^2 v = 0 \qquad (2)$$

after obtaining the potential distribution (v) from the above equation, one can find the electrical and current distribution from the folowing relationship:

$$\vec{E} = -\nabla v \qquad (3)$$

$$\vec{J} = \sigma(x,y,z).\vec{E} = \sigma(T).\vec{E} \qquad (4)$$

σ is the electrical conductivity of the material ,which its instant values are calculated as a function of temperature from the thermal analysis.

The electrical analysis is being performed in different instances of the armature's motion. Fig.(2) shows the current distribution (J) at 1.98 ms where the armature is about to be launched. Note that the maximum current passes through the sections of the rail which are behind the armature.

2 .3. MAGNETIC ANALYSIS

The goal of magnetic analysis is to find magnetic field distribution of the Railgun. The current distribution caused by the electrical analysis is considered as the entery point to this analysis. The effects of the 'Eddy current' created by the armature's motion is also added. In this analysis, first the magnetic potential vector (A) is obtained from the following relationship [3]:

$$\nabla \times (\frac{1}{\mu} \nabla \times \vec{A}) = \vec{J} \quad (5)$$

$$\nabla . \vec{A} = 0 \quad (6)$$

Then by using the obtained A , the current distribution by considering the Eddy effect is corrected in the following equation :

$$\vec{J} = \sigma\vec{E} = \sigma(x,y,z)\ [-\nabla v - \frac{\partial \vec{A}}{\partial t} + \vec{u} \times \vec{B}] \quad (7)$$

In this equation u is the armature velocity which is obtained from the mechanical analysis of the previous instant . B is the magnetic flow density and will be found from the following relationship:

$$\vec{B} = \nabla \times \vec{A} \quad (8)$$

This analysis is performed at different instances of the armature's motion and a sample of its result at 1.98 ms for (B) is shown in Fig.(3). It can be seen that this quantity is concentrated much more densely at the rear section of the armature rather than its front section. In reality, this factor creates the force to move it forward and causes the armature's motion.

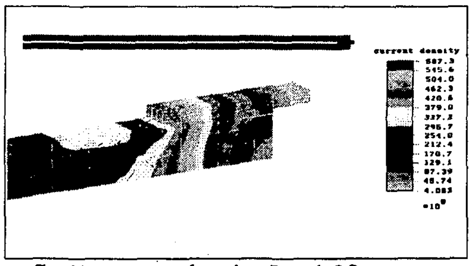

fig 2) current density J at 1.98 msec

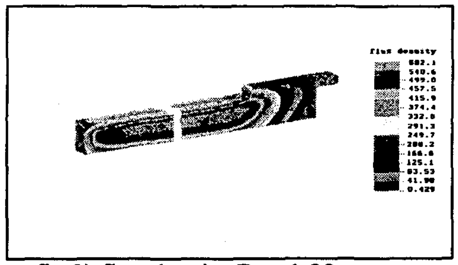

fig 3) flux density B at 1.98 msec

2 .4 . HEAT TRANSFER ANALYSIS

Using the obtained current distribution (J) from the magnetic analysis , we can find the power of ohmic attenuation in unit volume on each element which appears in form of thermal energy , from the following equation [4]:

$$Q = \vec{J}.\vec{J} / [\sigma(T)] \quad (9)$$

then temperature distribution is obtained from[5]:

$$-\nabla(k\nabla T) + \rho c(\partial T/\partial t) = Q \quad (10)$$

Where (k) is the thermal conduction, (ρ) is the mass volume and (c) is the specific heat of the material. By solving the above equation for the instantaneous motion of the armature, temperature distribution on the structure is obtained. This distribution is considered as the initial condition for the next instant. Also the electrical and thermal specifications of the material which are a function of temperature, are calculated from the given relationships and graphs in references [6,7] and is used for modeling of the next time step. Fig (4) shows a sample of obtained result from this analysis for temperature distribution at 1.98 ms. It can be detected that the temperature of the armature's rear section has increased from the room temperature (300 K) at the start of the motion to 910.3 K. Since the temperature at these points (and therefore at the other points) is less than the melting point of the rail and the armature, melting will not occur at these points. But it is highly probable to have shape changes there due to the heat. Fig.(5) shows the maximum temperature of the railgun at different instances. It can be observed that the rate of temperature increase at the finishing moments is much greater than other times.

on the armature is found and the acceleration , velocity , and location of the armature at every instant are calculated.

The results of the mechanical analysis is the force distribution on the structure, acceleration, velocity and the location of the armature at any instant. For example, the velocity of the armature in terms of time is shown in Fig. (5). It can be seen that the indicated 13.5 gr projectile is being launched with the velocity of 956.2 m/s at 1.982 ms from the end of the rail.

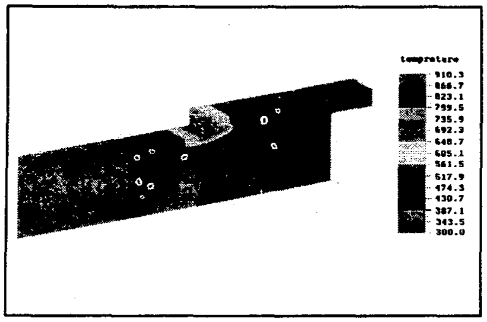

Fig 4) temperature dis. at 1.98 msec

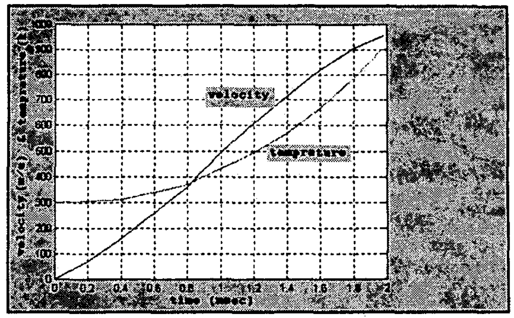

fig 5) velocity and max. temperature versus time

3. CONCLUSION

In this article we have presented a method by which the structure of a railgun can be solved in an inhomogeity condition (in which the specifications of the materials forming it are considered as functions of temperature) . This solution is essential for finding more realistic answers, because the temperature increase of the structure is so high that the changes in electrical and thermal specifications can nct be ignored. By using the present analysis in this article, any other model could be solved as well and the effects of dimensional changes and effect of voltage changes could be observed. Also, the wind resistance, friction and other factors could be considered to make the solution more precise and that will be one of our future tasks.

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