INHOMOGENEOUS EFFECTS OF TEMPERATURE CHANGES ON THE VELOCITY OF RAILGUN IN THREE DIMENSIONAL CONDITION

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Abstract In the Railgun which is used to accelerate objects, electrical energy is used to drive the system. In order to reach hypervelocities, 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 the ohmic attenuation and warms up various points and therefore changes the electrical, thermal and mechanical specifications of the structure. In this article, a method will be presented 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 are corrected at any instant. We have used three-dimensional finite element method with non-uniform meshing at any instant.

Key Words Railgun, Finite Element, Inhomogeneous, DCLM

چکیده در تفنگ ریلی که برای شتاب دادن اجسام بکار می رود از انرژی الکتریکی برای تحریک سیستم استفاده می شود. برای بدست آوردن سرعتهای زیاد باید از منبع تغذیه با انرژی زیاد استفاده شود که باعث ایجاد جریان فوق العاده ای روی ریل و آرمیچر می گردد. این جریان در اثر تلفات اهمی تبدیل به انرژی گرمایی شده، باعث گرم شدن نقاط مختلف و درنتیجه تغییر مشخصات الکتریکی، حرارتی و مکانیکی سازه می گردد. در این مقاله روشی ارائه می شود تا با استفاده از آن بتوان غیرهمگنی ناشی از تغییر دما در طول سازه را در نظر گرفت. در این روش، توزیع جریان در هر لحظه از زمان در ساختار بدست آمده، گرمای ناشی از آن محاسبه می شود و توزیع دمای سازه بدست می آید. ضریب هدایت الکتریکی، ضریب هدایت گرمایی و گرمای ویژه تابع دما در نظر گرفته شده و در هر لحظه حساب می شود تا مشخصات ماده تشکیل دهنده سازه در هر لحظه تصحیح گردد. برای حل در هر لحظه از روش عددی المانهای محدود سه بعدی با مش بندی غیریکنواخت استفاده نموده ایم.

INTRODUCTION

Railgun is equipment that is used to launch a projectile using electromagnetic forces. Its usage is in the fields of military weapons, nuclear physics, launching of objects to space etc. This equipment is

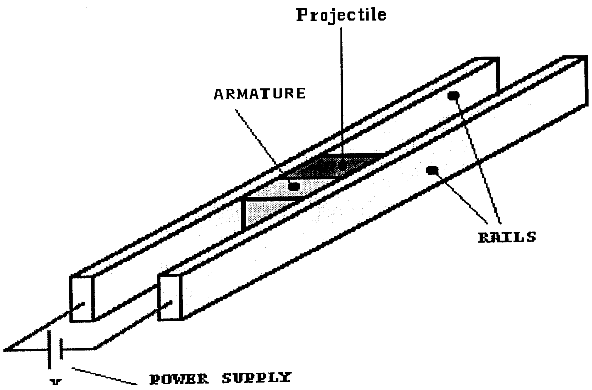


Figure 1. Simple structure of the railgun.

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 whose basic components are:

Rail It is made of two electrical conductors whose duties are conducting the current from the power supply to the armature and producing magnetic field around itself and in the armature.

Armature It is made of a fine conductor in different shapes. Armature itself can be considered as the projectile or as the accelerator for the projectile. The reaction of the armature's current to the magnetic field creates Lorentz force in the structure of the armature. This force causes armature to move with hypervelocity. This 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.

Power Supply and Switch It performs the task of supplying electricity to the system. Since the circuit resistance, which consists of rails and the armature, is small, this power supply and the switch should be able to inject a big current of about several hundred-kilo amperes or several mega amperes to the system. On the other hand, since the energy of armature's motion will be supplied by the energy of power supply, the power supply must be able to release great amount of energy at the moment of launching. The vast amount of current, which passes through the rail and the armature, causes them to warm up. This increase in the temperature changes the electrical and thermal specifications of the constituent parts and makes the structure an inhomogeneous media.

In the past, 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 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. The solution of the above structure for the armature's instantaneous motion requires various electrical, magnetic, thermal and mechanical analyses; we have used finite element method to solve it.

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 are performed and in each stage the obtained quantities are considered as the initial condition for the next stage.

Meshwork Considering the existing symmetry in Figure 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 the middle of the armature will be zero and -Vo will be acted upon the bottom rail. In our indicated model Vo is equal to 1250 volts. We must be precise in meshwork, because the dimensions of the mesh have inverse relation with the accuracy of the answer. Therefore, to increase the accuracy we must use smaller meshes. 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 we must use bigger elements in parts of the problem where quantitative changes are the function of the predicted answer and we must use smaller elements 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. 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.

Electrical Analysis The goal of electrical analysis is to solve Equation 2 with the conditions mentioned in the previous section:

$$\nabla^2 v = 0 \tag{2}$$

After obtaining the potential distribution (v) from Equation 2, we can find the electrical current distribution from the following relationships:

$$\vec{E} = -\nabla v \tag{3}$$

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

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

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

Magnetic Analyse 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 entry point to this analysis. The effects of the Eddy current created by the armature’s motion are also added. In this analysis, first the magnetic potential vector A is obtained from the following relationship [3]:

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

$$\nabla . \vec{A} = 0 \tag{6}$$

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

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

In Equation 7, 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:

$$\vec{B} = \nabla \times \vec{A} \tag{8}$$

This analysis is performed at different instances of the armature's motion of which a sample of its result at 1.98 ms for B is shown in Figure 3. It can

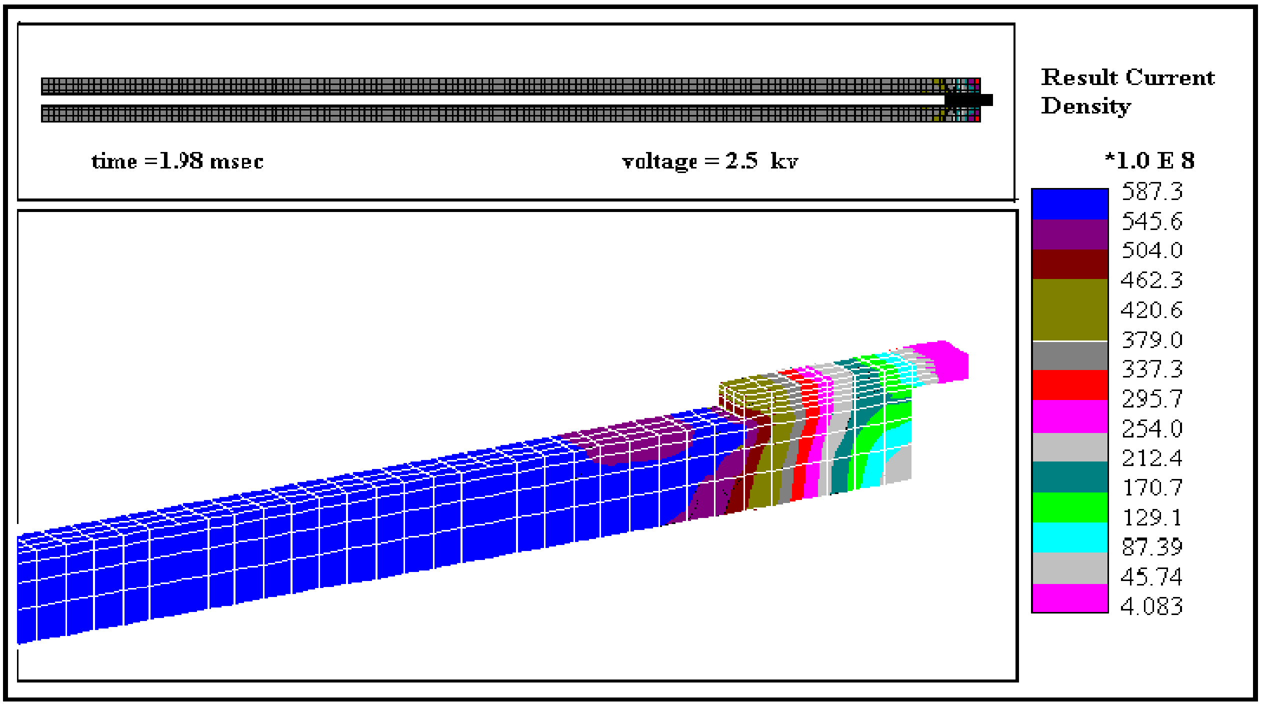


Figure 2. Current distribution (J) at t = 1.98 msec.

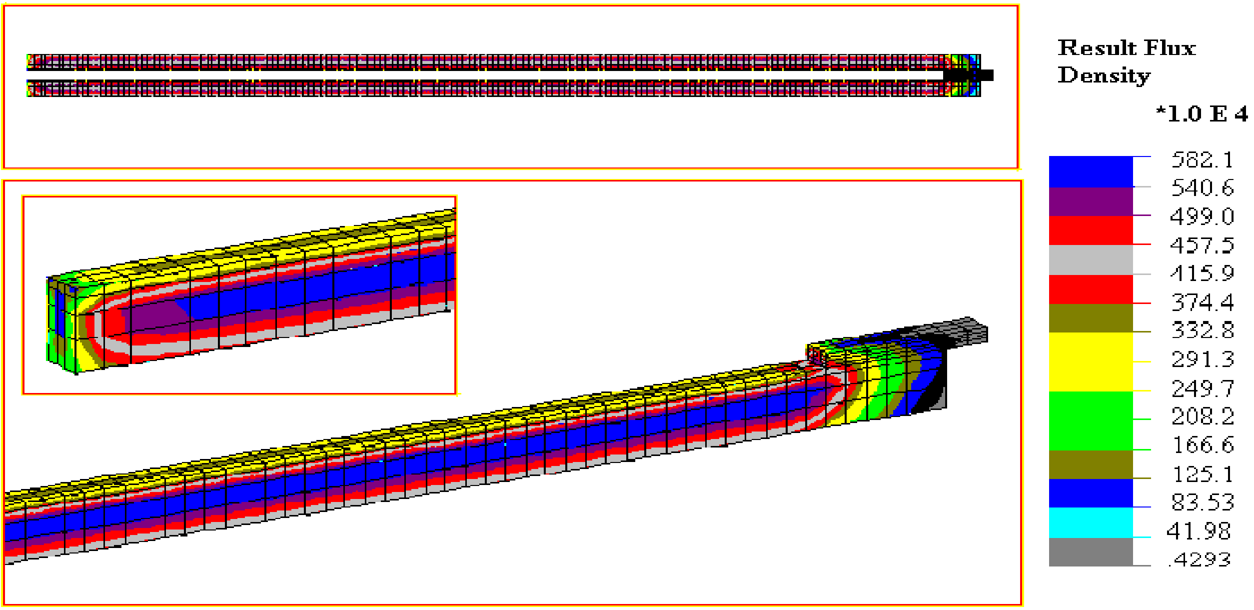


Figure 3. Flux density distribution B at t = 1.98 msec.

TABLE 1. Aluminum and Copper Properties.

	Aluminum	Copper
σ (mho/m)	$\dfrac{3.82\times10^{7}}{1+0.0039(T-300)}$	$\dfrac{5.8\times10^{7}}{1+0.0039(T-300)}$
c (J/K.kg)	0.486T+766	0.0987T+355
ρ (kg/m^3)	2700	8900

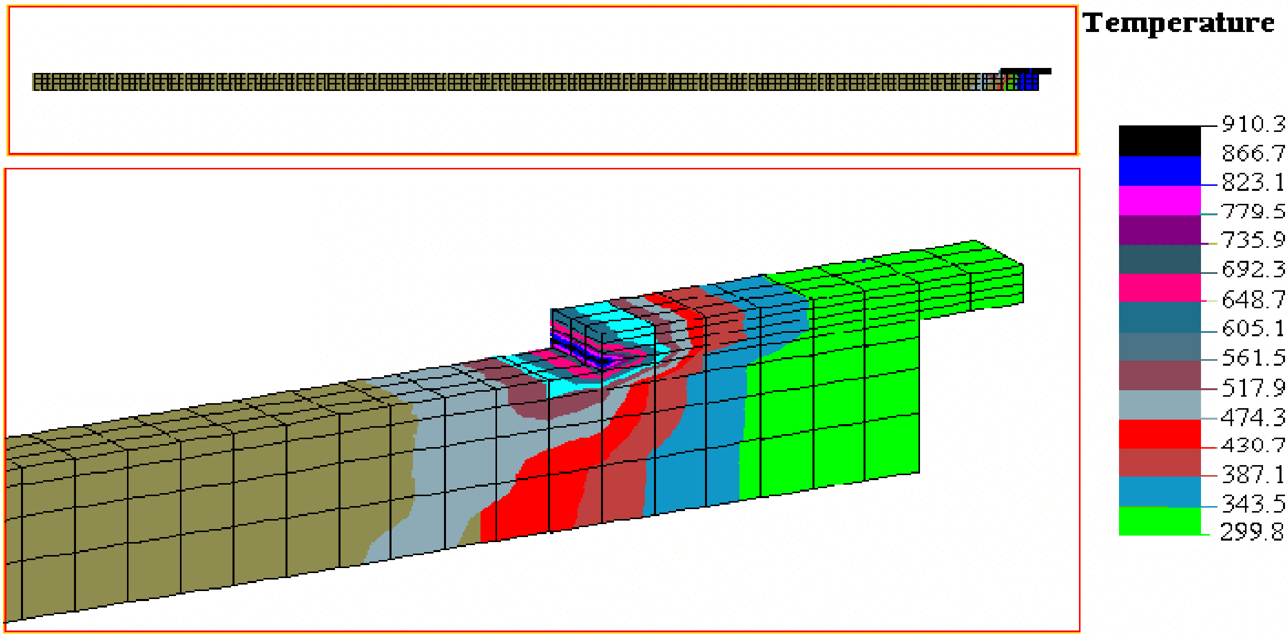


Figure 4. Temperature distribution T at t = 1.98 msec.

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.

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 that appears in the form of thermal energy from the following equation [4]:

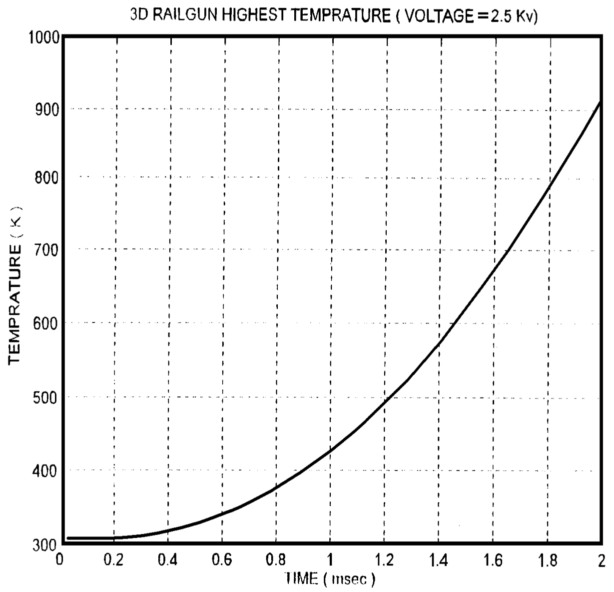


Figure 5. History of maximum temperature.

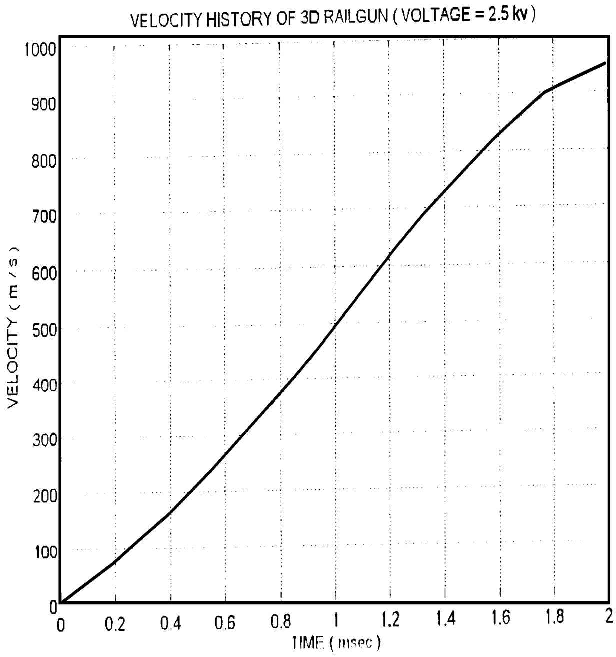


Figure 6. History of velocity.

$$Q = \frac{\vec{J}.\vec{J}}{\sigma(T)} \tag{9}$$

Then the temperature distribution is obtained from [5]:

$$-\nabla.(k\nabla T) + \rho c \frac{\partial T}{\partial t} = Q \tag{10}$$

Where k is the thermal conduction, ρ is the mass density and c is the specific heat of the material. By solving the above equation for the instantaneous motion of the armature, the 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 relationships and graphs in references [6,7] (Table 1) and are used for modeling of the next time step. Figure 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.

Figure 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.

Mechanical Analysis Using J and B quantities obtained from the magnetic analysis, we can calculate the exerted force on each element from Equation 1. If we sum up all the Fx forces on the armature's elements (they are effective forces on the accelerating armature), we can find the force exerted on the armature:

$$(F_a)_x = \sum_i (F_i)_x \tag{11}$$

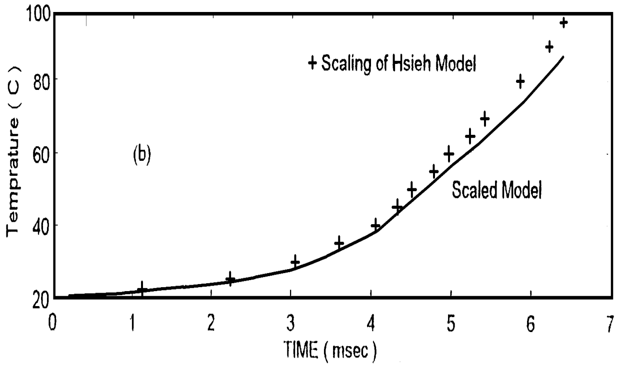
Having this force, from the mechanical relations, the acceleration, velocity, and location of the armature at every instant is obtained :

$$a_x = \frac{(F_a)_x}{m_a} \quad (12)$$

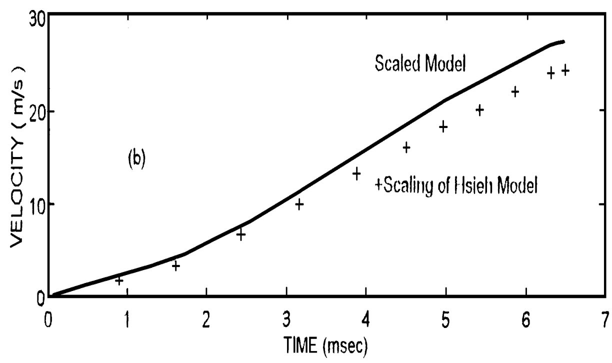
$$u_x = a_x \Delta t + u_0 \quad (13)$$

$$d_x = \tfrac{1}{2} a_x (\Delta t)^2 + u_0 (\Delta t) + d_0 \quad (14)$$

Where a_x is the acceleration, m_a is the mass, u_x is the velocity, u_0 is the initial velocity, d_x is the location, d_0 is the initial location of the armature and Δt is the time interval between the two successive solutions .



(a)



(b)

Figure 7. History of: (a) maximum temperature and (b) velocity. Hsieh model is shown with + sign and three-times scaled model is shown with solid curve.

The results of the mechanical analysis are 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 Figure 6. 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.

For justification of the correctness of the program and algorithm, a very small model is chosen with a known result that presented by Hsieh [5]. A similar model with three times larger dimensions is derived and solved by this method. By applying scaling coefficient [8] on Hsieh results, a good agreement was obtained between the two solutions. These results are compared in Figure 7.

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 not 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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