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Simulation of Electromagnetic Launcher Structure Using Finite Element Method

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Abstract

Electromagnetic launchers use electricity to fire projectile instead of conventional fuels. In this paper, three-dimensional Finite Element Method (FEM) simulation of the deformation of the rails and containment structure of the electromagnetic launcher is presented. The containment structure of the launcher has to counter the repulsive electromagnetic forces. The repulsive forces also push the rails apart and cause the armature to loose contact with rails. A three-dimensional model is prepared and studied to understand the behavior of the structural elements and the deformation of the different launcher components. The model is simulated by the finite element method using ANSYS commercial software. The simulation provides fundamental understanding that both static and dynamic responses of the launcher are important and needs to be studied. The simulation results of static analysis and the importance of dynamic analysis and its effects have been discussed in the present work.

Keywords: Hypervelocity Launcher, Deformation, Lorentz Force, Finite Element Method

Introduction

A typical electromagnetic launcher consists of two parallel current carrying rails and a projectile with a current carrying armature. As shown in figure 1, the electromagnetic launcher works on the principle of Lorentz force. The current is passed through rails; this creates the magnetic field between the rails. When current is passed through the current carrying armature, the interaction between magnetic field created due to current flowing through rails and armature current generates the Lorentz force. This Lorentz force accelerates the armature in turn projectile and fires the projectile.The repulsive electromagnetic forces acting on the rails can be treated as an engineering problem where rail is resting on the elastic foundation and subjected to the load which causes the deformation of the rails.The aim of this launcher is to fire a projectile with velocity of 2km/s and with increased range which could not be achieved with conventional guns. Hence these are also called as hypervelocity launcher. A review of the research efforts indicates that the technology is now maturing and moving from the laboratory prototypes to weapon platforms. When repulsive force pushes the rails apart, armature loses contact with the rail and an arc is created which could damage the armature and rail and it may not fire the projectile at all. Hence, it is necessary to find out the deformation of the rails when repulsive force is acting and making sure that that contact between the rails and the armature is maintained.

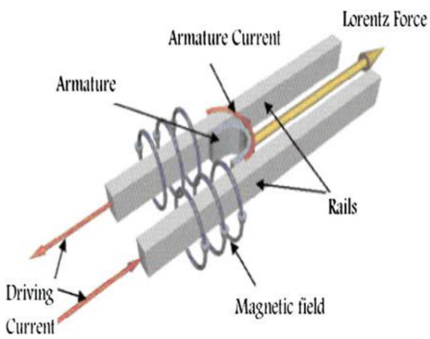

Figure 1: Working principle of launcher

Tzeng [2003] developed a model to investigate the dynamic response of an electromagnetic railgun, induced by moving magnetic pressure during launch of projectile. The critical velocity derived affects life of railgun and was found to be dependent on cross section of geometry, mechanical properties of rail and containment structure. Ghassemi et al. [2008] carried out experiment on an electromagnetic launcher. Armature is moved forward by the dynamic force created by magnetic field. The purpose is to find out effect of armature velocity and to determine the magnetic pressure and armature velocity with respect to position and time. Maximum volumetric forces take place where highest magnetic field gradient occurs. Littlefield et al. (2006) studied one of the problems in an electromagnetic railgun is high electromagnetic repulsive force that pushes rails apart and causes rails to lose contact between them. High modulus fibers are used to fabricate thin and light weight structure. The analysis is done by building two-dimensional static finite element analysis model and only quarter model is used with symmetry boundary conditions. Lewis et al. [2006] studied the dynamic and strength based optimised design of hypervelocity electromagnetic launchers. When projectile moves along the rails at critical velocity, creates damaging resonant regimes along rails which reveal increased displacement and stress which shortens the life of launchers. Kacianausakas et al**.** [2013] presented the three-dimensional FEM simulation of the dynamic behaviour the electromagnetic railgun housing. The housing is designed such that it has to counter the repelling forces acting on the rails. This is done by the discrete steel bolts. Gildutis et al. [2012] studied the mechanical response of the railgun structure to the magnetic forces acting on the rails. They modeled rail as a cantilever beam on the elastin foundation. The whole structure is designed to withstand the high repelling force between the rails. The rail deformation has crucial effect on sliding performance of the armature. Batteh et al. [1993] studied the effects produced by time-varying current profile on a time dependent, one-dimensional model for describing the transient behaviour in railgun plasma armature. The model developed accounts for plasma properties that vary not only along acceleration direction but also in direction normal to rail surface. Khershed et al. [2007] studied the railgun barrel material performance under significantly high current conditions for number of shot on multiple launches. Material analysis was conducted on rail samples from four sets of experiments involving increasing number of shots. Difference in the current density and temperature causes uneven groove size and uneven armature-rail gap. Jianxin et al.(2012) found out that small launching efficiency and less working life are the critical issues in applying electromagnetic launcher technology in civil and military use in future. The deflection of the rails is highly affected by the shape of the rails when electromagnetic force load acts on it. Generally rectangular cross section rails are used but non rectangular cross section rails show some performance improvement. From the papers reviewed, it has been observed that not much simulation work has been done for the launcher and analysis could give fair idea about the strength of the launcher and response of the different launcher components when repulsive forces act. The present work includes the effects of the repulsive forces on the launcher and its components.

Modeling of Electromagnetic Launcher

A three-dimensional model of the electromagnetic launcher has been generated in the ANSYS work bench geometry and same model is used for the analysis. It consists of different components assembled together. Two rails along with side support plates form the bore of the electromagnetic launcher through which projectile along with armature will move. Rails are surrounded at top and bottom with the top support plate and bottom support plate. Material used for rail is copper while side support plate, top support plate and bottom support plate are made of insulating material GRP. To hold these components together, containment structure is made. The containment structure consists of side block and retaining plates and is made of material steel. M48 bolts hold the retaining plates and side block together. The whole gun will be placed on the stand which has wheels for the movement. The working principle of all the electromagnetic launcher designed so far and loading conditions on the rails in terms how they are applied is basically same. When the electromagnetic force acts, rails are compressed against the outer containment structure. The force (magnetic load) at the front location of the armature/rail interface is presumably discontinuous. This discontinuity of forces can cause local bending and shear stresses in the rails near armature location. A static analysis is performed to check the mechanical response of the containment structure and rails when electromagnetic force acts. A force of 1MN is applied on the rails which represent the electromagnetic force. The magnitude of the repulsive force is obtained by

$$F = \int \frac{\mu_0 i}{4\pi} \frac{d\vec{l} \times \vec{B}}{r^3} \quad \text{……….} (1)$$

This equation is known as Biot-savart law and it gives magnetic field generated by current. It relates magnetic field to magnitude and direction of the current. In this equation, B is the magnetic field generated at position r by a steady current i.

Table 1: Mechanical properties and geometric parameters of rail and containment

PART	MATERIAL	MODULUS OF ELASTICITY	COMPRESSION STRENGTH	DENSITY	DIMENSIONS
Rail	Copper	110GPa	600MPa	8960kg/m^3	Height- 35mm Width- 60mm
Insulating components	Glass reinforced plastic(GRP)	24GPa	-	1850 kg/m^3	-
Containment structure	Steel	200GPa	-	7900 kg/m^3	-

Electromagnetic repulsive forces push the rails apart and cause rails to loose contact with the armature. If contact between armature and rails is lost, spark will be created due to high intensity current and it could melt the armature. This will cause problem in smooth working of the launcher and launcher may not fire the projectile at all. Hence static analysis of the launcher is necessary to find out the deformation of different launcher components and use suitable containment structure if deformation is above the permissible value.

Boundary Conditions

The launcher is placed on the stand. Hence a fix support at the bottom surface is applied. The bolts used in the containment structure are prestressed with force of 5000 N. Pre-stressing is done to minimize the effects of stresses generated due to repulsive force. When repulsive force will act on the launcher, first it will relieve the stresses generated due to pre-tensioning and then further stresses will be developed. This value of pre-tensioning is decided from the yield strength of the material used for the launcher. Hence, pre tensioning force of 5000 N is given to the each bolt. Force of

1MN equivalent to repulsive electromagnetic force is applied on the rails. Figure 2 shows different forces applied and position of fix support. ‘A’ is fix support given at the bottom of the launcher. ‘B’ and ‘C’ are the repulsive electromagnetic force on the rails. ‘D’, ‘E’, ‘F’ and ‘G’ are pre-tensioning forces applied on the bolts.

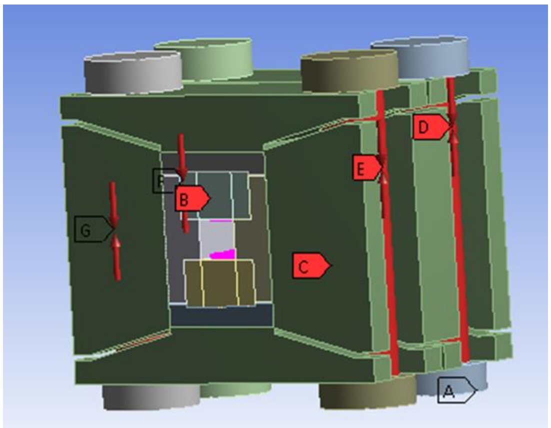

Figure 2: Boundary conditions

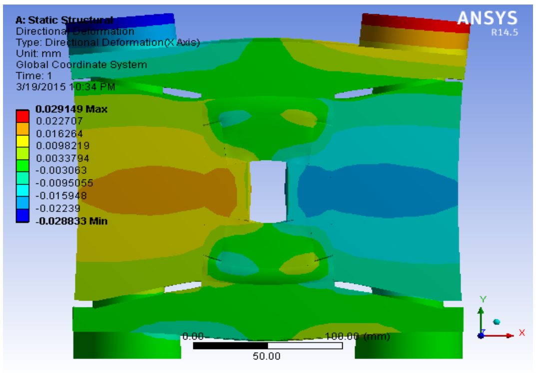

Figure 3: Deformation in X direction

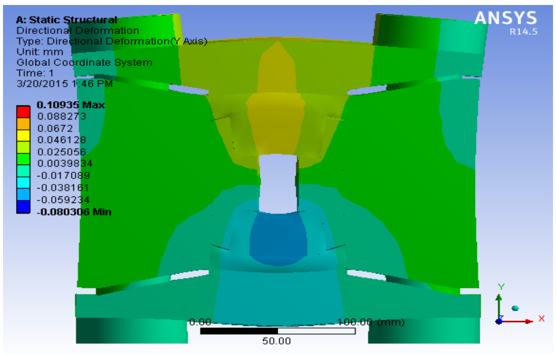

Figure 4: Deformation in Y direction

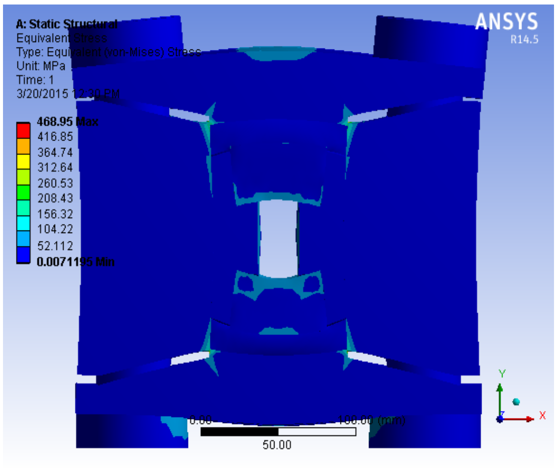

Figure 5: Stress distribution in the structure

The dynamic response of the rails is of concern since very large strains have been observed in the conventional tank guns due to resonance occurring in the structure. The dynamic response of the rails becomes critical for light weight barrel designs and for increased projectile velocity. The electromagnetic launcher being both lightweight and able to launch projectile at hypervelocity, dynamic analysis should be considered in the containment structure design. Figure 6 shows that cross section of the rail has been considered which is rectangular and is supported mechanically by rigid structure. The structural response of the rail can be modeled as a beam sitting on elastic foundation. So in the present case rail is considered as beam and containment structure and insulating material is considered as elastic foundation. The magnetic force travelling at the speed of projectile on the rails can be expressed as heavy side step function. The governing equation for the launcher subjected to moving load can be derived as follows [Tzeng, 2003]

$$m \frac{d^2\omega}{dt^2} + EI \frac{d^4\omega}{dx^4} + k\omega = q\,[1-H(x-Vt)]\,, \qquad \ldots\ldots\ (2)$$

where, 'ω' represents the lateral displacement dependent upon time t and axial position coordinate x, 'm' represents mass per unit length and is equal to density of the material. 'I' is the moment of inertia of rail cross section and 'E' is the modulus of elasticity of rail material. The term 'q(1-H(x-Vt))' represents the magnetic load front travelling along the rail with constant velocity. Equation (2) is solved using separation of variables method and critical velocity for rail of rectangular cross section having width b, thickness h, area A=b*h and moment of inertia $I=bh^3/12$ is found out. Equation (3) gives the critical velocity for the launcher subjected to moving load and it is observed that the critical velocity is function of rail geometry, density and the modulus of elasticity. Critical velocity can be calculated using equation (3) for particular structure and obtained value would be an indication if the design is safe or it requires any modifications [Littlefield et al., 2006]

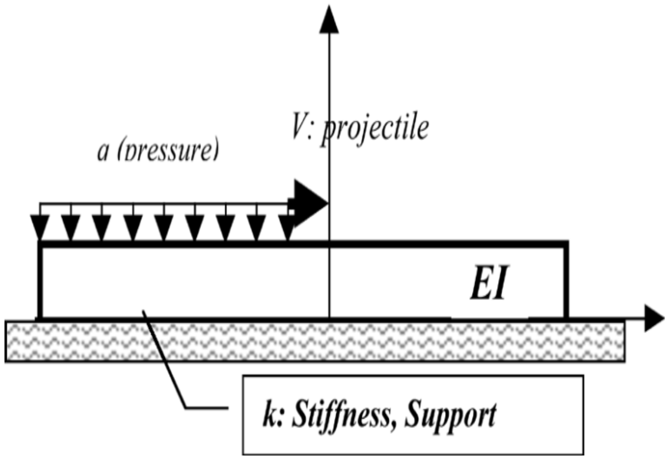

FIGURE 6: Rail and moving load

$$V_{cr}^{\ 2} = \frac{1}{\sqrt{3}} \frac{1}{\rho} \frac{\sqrt{h}}{\sqrt{B}} \sqrt{E\sqrt{k}} \ \ldots\ldots\ldots\ldots \ (3)$$

where 'V_{cr}' is the critical velocity, 'ρ' is the density of the material, 'k' is the elastic constant of foundation. Once the critical velocity is known using equation (3), it is compared with the velocity of the projectile and it is confirmed that both velocities are not same since it could create resonant regimes in the structure and could damage the launcher. Accordingly either changes in the material property and geometry or velocity of the projectile are made.

Results and Discussions

Force of 1MN equivalent to electromagnetic repulsive force as shown in figure 2 is applied on the inner surface of the rails of the launcher and the shape of the deformation is observed which is as expected. As the launcher model is symmetric about X and Y axis, figure 2 and 3 shows that the deformation pattern is also symmetric and only value of deformation is different due to fix support at the bottom surface. The deformation should not exceed 0.5mm since it will create gap between armature and the rail. From figure 3 maximum value of deformation in positive X direction is found to be 0.02941mm and in negative X direction is 0.0288mm. The displacement obtained is small and within the allowable limit which indicates that the stiffness of the containment and rails is sufficient enough to avoid excessive deformation. Figure 4 shows the displacement variation of the launcher components in Y direction. Maximum value of displacement is below 0.5mm hence it is within the allowable limit. The stress distribution obtained in the structure as shown in figure 5 gives maximum stress of 468.95MPa. Rails are the main component in the launcher with compressive strength of 600MPa. Hence, the stress getting induced is within allowable limit as the compressive strength of the material used for rail is above stresses getting induced due to electromagnetic repulsive force. Stress caused due to vibration and dead weight is not considered in the analysis.

This work is focused on the effect of the electromagnetic repulsive force on rails and surrounding containment structure. Hypervelocity launchers are subjected to high stress and strains due to movement of armature with high velocity on the rails. These stresses can be minimized by using suitable containment structure and finding the critical velocity of the armature. Also, it can be seen that containment structure helps in keeping rails intact when the repulsive force acts on the structure. Results obtained by simulation shows that stresses in our case are within the permissible limit of the structure. Also the strength of the structure depends on the material used for different components.

Conclusion

Numerical simulations are carried out in the present work to observe the effect of the electromagnetic repulsive force on rails and surrounding containment structure. A static analysis is carried out to explore the stress distribution and the behavior of deformation when repulsive force acts on the structure. Results obtained by simulation shows that stresses and deformation in this case are within the permissible limit of the structure. It is found that the strength of the structure depends on the material used for different components and the critical velocity dependent on the shape of the rails. Hence, different shapes of the rails can be used to vary the critical velocity and minimize the deformation of the rails. The results obtained in the present study will be highly helpful to carry out further dynamic analysis of the system.

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