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A MULTIPHYSICS MODEL OF AN ELECTROMAGNETIC LAUNCHING SYSTEM[6]

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Abstract: *A three-dimensional model of an electromagnetic launching system is developed. The model consists of electrical and mechanical parts and it is a multiphysics system. This is the first step of the research and the model is theoretical. It can be the basis for future investigations, optimizations and physical prototypes manufacturing. Time diagrams of the coil current, the electromechanical force acting on the projectile, the position of the projectile, and the velocity of the projectile are created, compared, and analyzed.*

Keywords: *Launching System, Multiphysics Model, Electromechanical Force, Position, Velocity*

INTRODUCTION

Electromagnetic launching systems (EMLS) are an alternative to the chemical launchers. The utilization the chemical energy of the fuel has high cost and negative environmental impact. EMLS provides viable projectile propulsion with reasonably low cost and minimal environmental drawbacks. Therefore, they are used in many modern fields such as space launchers (Z. Lin et al., 2020), (McNab, I. R., 2003), transport and drive systems (Wu S, Cui S., 2021), and weapons (Y Luo, Long L., 2020), (Wu S, Cui S., 2021).

When electric current energizes solenoid coils, an electromagnetic force occurs caused by Fleming's right-hand rule. The electromagnetic force of the coils attracts and launches the projectile (Kim S., Kim J., 2016). Fig. 1 illustrates the schematic and operational principles (Valentin, G. et al., 2019).

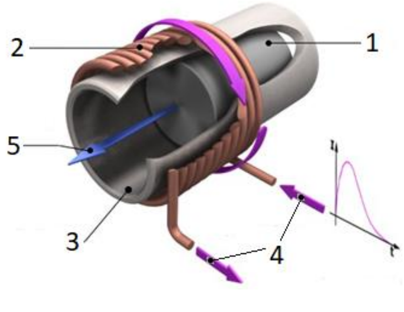

Fig. 1. The basic elements of electromagnetic launching systems: 1 – a projectile, 2 – a drive coil, and 3 – a flyway tube. The directions are marked thought arrows, as follows: 4 – the direction of the coil current, and 5 – the direction the projectile velocity.

Electromagnetic launching systems combines several physical fields. Therefore, modelling and investigations of EMLS requires modern high-tech approaches, methods and tools. The aim of this research is to develop a three-dimensional multiphysics model of a simple electromagnetic launching system and to investigate the force acting on the projectile. For research such as combining different physical fields, an appropriate software system must be selected.

The finite element analysis system ANSYS offers a module named MAXWELL. Fig. 2 shows finite element model of coils and projectile created with the help of this module (Kim S., Kim J., 2016). Since the velocity is proportional to the number of solenoids, it is hard to control the muzzle velocity of coil gun.

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Therefore, in (Kim S., Kim J., 2016) is used the two-stage approach. The first solenoid coil used the optimally-designed model of the single-stage coil gun system, and the second solenoid coil uses the velocity of the single-stage coil gun system as its initial velocity.

The system COMSOL Multiphysics is one of the leading cross-platform finite element analysis systems. It provides a workflow for electrical, mechanical, fluid, acoustics, and chemical applications. In (Paudel, N., 2016) is presented a study in the area of particle dynamics in electromagnetic fields – Fig. 3. Therefore, it is used as a basis for the model developing realized in this research.

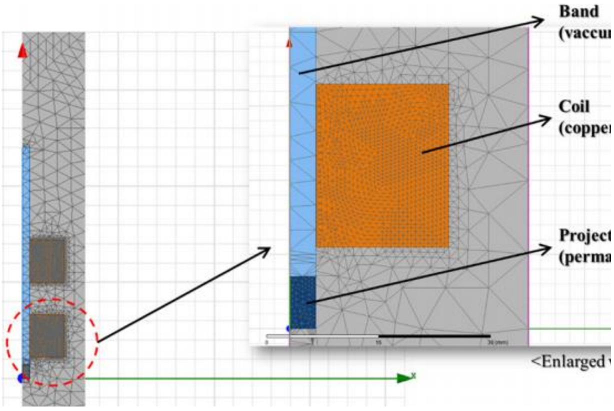


Fig. 2. Mesh plot of a finite element model of coils and projectile.

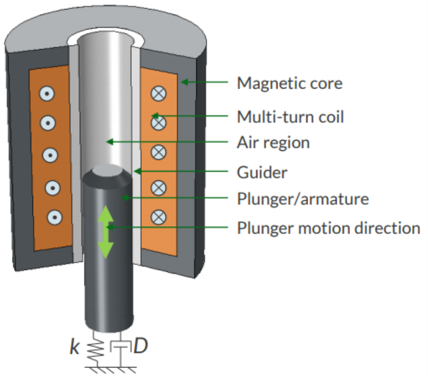


Fig. 3. Model of a linear electromagnetic plunger

DESCRIPTION OF THE DEVELOPED MODEL

The structure of the developed electromagnetic launching systems model is shown on Fig. 4.

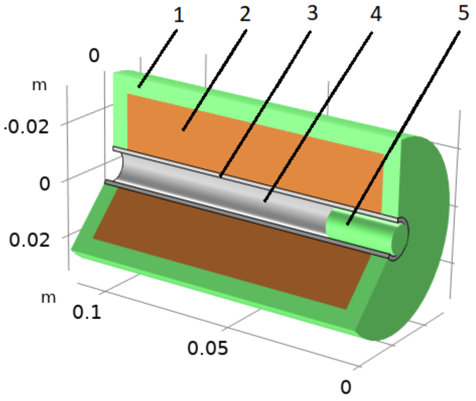


Fig. 4. A scheme of the model developed: 1 – magnetic core, 2 – multi-turn coil, 3 – nonmagnetic guider, 4 – air region, 5 – magnetic projectile

For the projectile launching, a current impulse must be applied. The limit value can be calculated by Onderdonk’s equation:

$$33\left(\frac{I_f}{A}\right)^2 s = log\left(\frac{T_m - T_0}{234 + T_0} + 1\right), \tag{1}$$

where: I_f is fusing current in amperes, A – wire area in circular mils, s – melting time in seconds, T_m – melting temperature of wire in °C, and T_0 – ambient temperature in °C. For the material of the AWG 12 commercial coil, the fusing current according to Eq.1 is $I_f = 3700$ A (Su-Jeong, L. et al., 2016). A safety margin is applied and the coil current impulse in this research is

$$I = 3000\, Rect(t), \tag{2}$$

as can be seen on Fig. 5.

The electromagnetic force on the projectile due to the described by Eq. 2 current impulse is calculated through COMSOL using the Maxwell stress tensor method. This electromagnetic force is then added to the dynamical equation of motion of the projectile. This forms a system of two first order differential equations, as follows:

$$\left| \begin{array}{l} M\dfrac{d}{dt}v(t) + Dv(t) - F(t) = 0 \\ \dfrac{d}{dt}p(t) - v(t) = 0 \end{array} \right. ,$$

where: M is the projectile mass, D – a coefficient accounting the air resistance as a viscous friction, F – the electromagnetic force on the projectile, v – the projectile velocity, and p – the projectile position.

RESULTS

The results from FEM simulation performed (Fig. 5) shows that the projectile velocity reaches 20 m/s for 4 ms, while the displacement is about 120 mm. With the start of the coil current impulse, the electromagnetic force impulse on the projectile also has a start and reaches 2 kN at time 0.3 ms. The time points of starting or stopping of the impulses are characteristic points. The magnetic flux density color maps for these points are shown on Fig. 6 and Fig. 7.

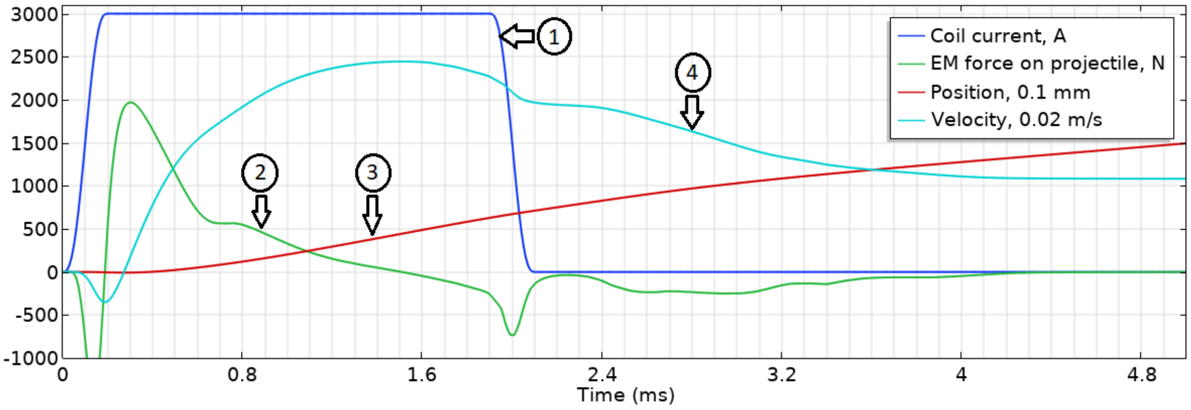


Fig. 5 Time diagrams of the results obtained: 1 – the coil current, 2 –the electromagnetic force on the projectile, 3 – the projectile position, 4 – the projectile velocity.

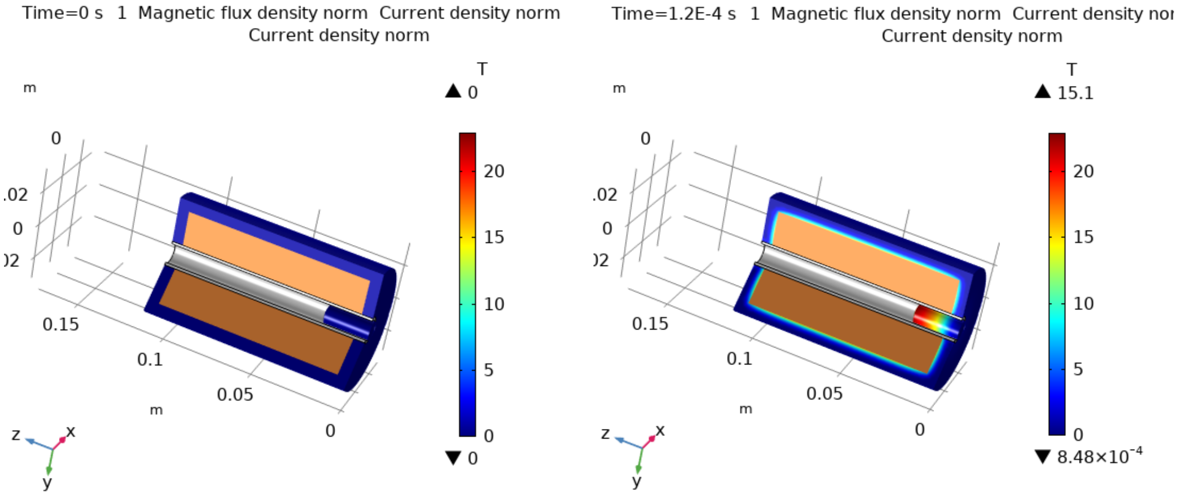
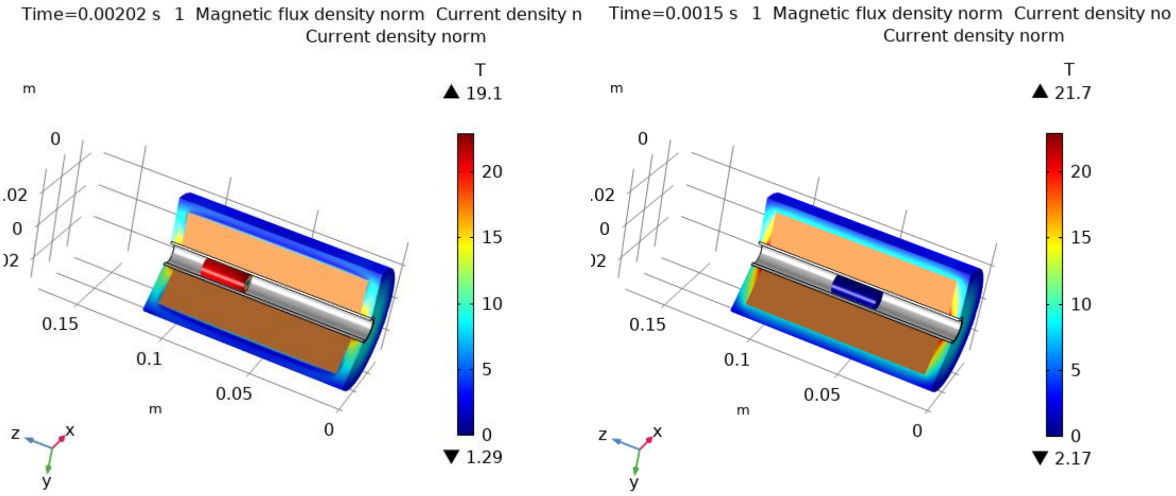


Fig. 6. The magnetic flux density for characteristic moments of time: before the launching (left) and at the raising front of the coil current impulse (right).


Time=0.00202 s 1 Magnetic flux density norm Current density n
Current density norm

Time=0.0015 s 1 Magnetic flux density norm Current density no
Current density norm

Fig. 7. The magnetic flux density for characteristic moments of time: at the falling front of the coil current impulse (left) and about at the middle of the acceleration process (right).

CONCLUSIONS

A basic model of an electromagnetic launching system is successfully developed. The model is a multiphysics system and contains electric and mechanical parts. It can be useful for future investigations, optimizations and physical prototypes manufacturing.

The electromechanical force acting on the projectile is determined using the Maxwell stress tensor method. The dynamical equation of the motion of the projectile under the action of this force is formed and solved. As a result of this the projectiles position and velocity are obtained. They are presented through time diagrams and are discussed. The maximum projectile speed is determined as well as the displacement necessary to reach it. The time points of starting or stopping of the coil current impulses are characteristic points. So, the magnetic flux density for these points is obtained and presented through color maps.

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