AN ELECTROMAGNETIC LAUNCH SYSTEM FOR UAVs

Laurian GHERMAN

Department of Electronics and Informatics, Faculty of Aeronautical Management,
“Henri Coandă” Air Force Academy, Brasov, Romania

***Abstract**: This paper presents a new design of a launch catapult based on electromagnetic energy for tactical UAVs. This technology is under development to launch projectiles with high velocity but it has theoretically proved the possibility to launch also UAVs. The second part presents a theoretical approach necessary to find the expression of force under certain approximation for E-shaped electromagnetic launch system design. Based on the theoretical results, I have built a physical model in order to examine the behavior of this design under laboratory conditions. After that, I have created a computer model calibrated to reproduce the behavior of the physical model with errors below 1%. I have used an interactive software package based on the finite element method (FEM) to analyze, solve three-dimensional electromagnetic field problems and simulate the E-shaped design’s behaviors. The last part of the paper present the results of simulation which prove the possibility of using the E-shape design to launch different masses with a desired speed.*

***Keywords**: UAV, coilgun, induction, Lorentz force, electromagnetic launch system).*

1. INTRODUCTION

Nowadays UAVs have recorded an increased rate of development and so they can now its cover a large spectrum of missions. If we compare UAVs based on dimensions we can see that there are big UAVs used to operate at global level through mini UAVs used inside buildings. The big UAVs are operated almost like a manned aircraft, fact which implies the existence of an airport infrastructure and a runway for take-off and landing. The mini UAVs can be launched by hand. Between these two extremes, there is a category of UAVs used at tactical level which cannot be launched by hand and the cost to build a runway is very high. These UAVs are launched using RATO (rocket assisted take-off) or catapults. These installations are a good solution because:

- the UAVs can be launched without any infrastructure;
- because the fuel is not used for launching the payload weight or the mission time can be increased;
- this approach is environmentally friendly.

The catapult installations use different kinds of energy to accelerate the UAVs like:

- mechanical energy stored in springs or rubber bungee;
- pneumatic/hydraulic energy produced by cylinders and pistons;
- electromechanical energy produced by electrical motors.

All these installations are made by using many parts which increase the complexity and require a lot of maintenance in order to be functional. Also these installations are not part of the automatic loop used to control the UAVs. In order to improve the launch system this should have few moving parts to reduce maintenance costs and should be powered by electric energy in order to be easily integrated into the automatic control loop.

A possible solution can be an electromagnetic launch system like, the railgun or coilgun. These systems were initially developed to accelerate projectiles at very high speeds. Because the guns based on chemical energy achieved their maximum possibilities the researchers found a new way to increase the projectile speed from 1.5 km/s to 8 km/s. The first direction of research and the most developed is the railgun design. This design consists of two parallel DC powered rails, and a sliding armature between them. This armature is rigidly coupled with the projectile.

The Lorentz force is used to launch projectiles. A good approximation of the force produced by this design is given by the expression (*Railgun*, 2011):

$$F = \frac{\mu_0}{2\pi} I^2 \ln\frac{d}{r} \quad (1)$$

where: μ_0 - magnetic constant $4\pi \times 10^{-7}\ \frac{N}{A^2}$; I - the current through system (A); d - the distance between rails; r - the radius of the rails.

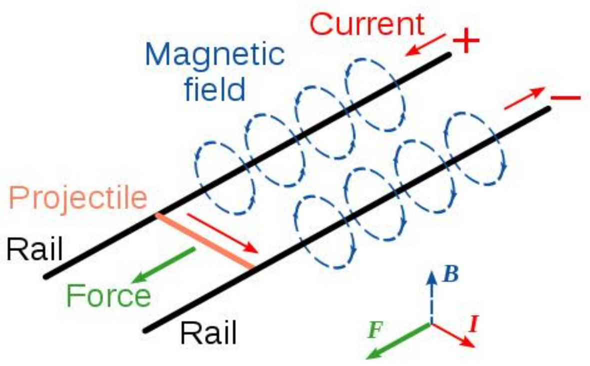

Fig.1 Rail gun design (*Railgun*, 2011)

Because this system is in an advanced stage of development and the results obtained are good, it was used like a possible solution to replace the steam catapults on US carriers. This technology proved that it is capable to accelerate an F18 airplane to the takeoff speed on the same length like the steam catapult.

Despite these achievements the railgun technology has a few drawbacks. The main drawback is the sliding contact between armature and rails. Because of this the rails must be replaced after a certain number of launches. Also because the rail is like a straight conductor a very high current is necessary to produce the desirable magnetic flux density B. As a result the power source should be able to provide a large amount of energy. Taking into consideration these drawbacks this technology is not suitable yet to launch UAVs but it can do it. So in order to use an electromagnetic launch system to launch UAVs another approach should be taken into consideration. This new approach should eliminate the sliding contacts and use less energy. To do this, such a system should be based on induction and magnetic flux density B should be created by a coil.

Based on this observation I have developed a new coilgun. This design is an improvement of an older, well known design like "Thomson Jumping Ring" adapted to launch projectiles. This approach solves most of issues related with the railgun system presented above:

1) The magnetic flux densities B is created by a coil and a magnetic circuit made by soft magnetic materials;
2) The current necessary to produce desirable magnetic flux densities B is less than in the case of the railgun design;
3) The armature is a ring made of aluminum and the UAVs can be attached by ring.
4) The current is induced into the ring so there are not contacts between the armature and coil or magnetic circuits;
5) The Lorentz force produced is only in axial direction and it is possible to use all the available energy to accelerate the ring.

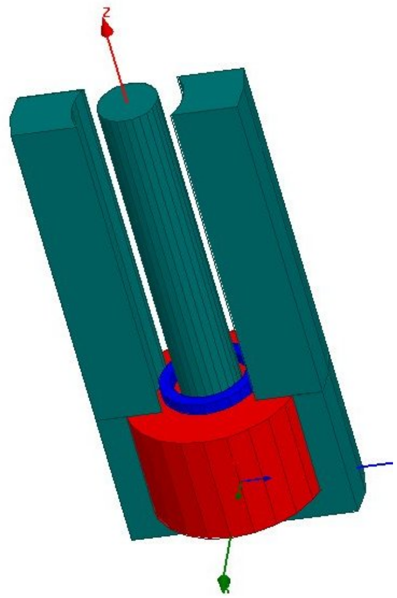

Fig.2 "E-shaped" coilgun design

In Gherman *et al.* (2011:725-729) I have demonstrated the superiority of "E-shaped" design compared with "Thomson Jumping

Ring" design. Despite the fact that this design is still under development, it has demonstrated the possibility to produce enough force to launch an UAV. This paper presents this design and the results obtained under laboratory conditions.

2. THE "E-SHAPED" DESIGN THEORY

This device is based on two fundamental laws: the Faraday law (induction) and Lorentz law (force).

$$\varepsilon = -\frac{d\varphi}{dt} \tag{2}$$

If there is N number of turns in the coil with the same amount of flux flowing through it, hence:

$$\varepsilon = -N\frac{d\varphi}{dt} \tag{3}$$

where: N – number of turns of wire in coil.

Lorentz's force is produced by a current carrying conductor (in this case the ring) present in a uniform magnetic field of flux density B (in this case into the airgap between columns). Dependent upon the direction of the surrounding magnetic field, the force induced is given by (in this case in axial direction repulsive sense):

$$F = i(l \times B) \tag{4}$$

where: i – represents the current flow in the conductor; *l* – length of wire, with direction of *l* defined to be in the direction of current flow; B – magnetic field density

The goal is to create an electromagnetic launch system based on the "E-shaped" design which produces a Lorentz force at a maximum possible value under certain condition in order to achieve a specific muzzle velocity necessary to launch different UAVs with different masses.

First, I chose the shape of armature circular because *l* is maximum in the case of a circumscribed circle of a square. Compared with a square it can be written:

$$\frac{\pi r}{2} > r\sqrt{2} \tag{5}$$

where: r - the radius of the circle.

I calculated the dimensions of the magnetic circuits in order to allow the saturation only inside the coil (the saturation cannot be avoided). I calculated the air gap at a minimum possible to allow the movement of the ring without any friction. The dimensions of the "E-shaped" launcher are:

1) coil height H_c=58 mm; inner diameter d_c=40 mm; outer diameter D_c=60 mm; number of turns N=300; winding made of cooper wire.
2) ring height H_r=5 mm; inner diameter d_r=40 mm; outer diameter D_r=50 mm; made of aluminum; mass m_r=$10 \cdot 10^{-3}$ kg.
3) the coil is powered by a voltage source of 240 V/ 50 Hz.

Because magnetic flux density B is a function of linkage flux Φ_l and the induced current inside the ring is a function of speed variation of a fraction of linkage flux, mutual coupled flux, $\Phi_M \left(\frac{d\Phi_M}{dt}\right)$ a maximum linkage flux must be created in order to achieve a maximum force.

First, let us consider the device without the ring. The coil is powered by a sinusoidal voltage.

$$U_{1m}\sin(\omega t + \alpha_0) = R_c i_c + N\frac{d\varphi_c}{dt} \tag{6}$$

Where: U_{1m} – maximum value of source voltage; α_c – phase angle; R_c – electrical resistance of coil wire; i_c – intensity of current in coil wire; N – number of turns in coil; φ_c – magnetic flux created by coil.

For the limit case when $R_c = 0$ it can be written:

$$U_{1m}\sin(\omega t + \alpha_0) = N\frac{d\varphi_c}{dt} \tag{7}$$

The solution of (7) is:

$$\varphi_c = -\frac{U_{1m}}{N\omega}\cos(\omega t + \alpha_0) + C \tag{8}$$

If considered at t=0 $\varphi_c = 0$ then:

$$C = \Phi_{cm}\cos\alpha_0 \tag{9}$$

So, the expression of magnetic flux can be written:

$$\varphi_c = -\Phi_{cm}\cos(\omega t + \alpha_0) + \Phi_{cm}\cos\alpha_0 \tag{10}$$

Where the first term from the right side is the ac component and the second term is the dc component. For us the most favorable situation is at $\alpha_0 = 0^0$ or $\alpha_0 = 180^0$ degrees when:

$$\Phi_c = 2\Phi_{cm} \tag{11}$$

For a given voltage, the maximum magnetic flux is created in transient regime if the electrical resistance of the coil is zero and the coil is fired at 0 or 180 degrees. Under these conditions, the transient regime becomes steady state. Now let us consider the device with the ring in a static position. The coil is powered by the same sinusoidal voltage at 0 degree phase. The following system of equation can be written:

$$R_c i_c - u_1 = -L_c \frac{di_c}{dt} + M\frac{di_r}{dt} \tag{12}$$

$$R_r i_r + 0 = -L_r \frac{di_r}{dt} + M\frac{di_c}{dt} \tag{13}$$

where: L_c – coil inductance; L_r – ring inductance; M – mutual inductance.

In order to find out the expression of ring current, let us assume $R_c = 0$ and $R_r = 0$. The system of equation becomes:

$$u_1 = L_c \frac{di_c}{dt} - M\frac{di_r}{dt} \tag{14}$$

$$L_r \frac{di_r}{dt} = M\frac{di_c}{dt} \tag{15}$$

and

$$\frac{di_r}{dt} = \frac{M}{L_c L_r - M^2} u_1 \tag{16}$$

The induced current in the ring is:

$$i_r = \int di_r = \int \frac{M}{L_c L_r - M^2} U_{1m} \sin \omega t\, dt \tag{17}$$

$$i_r = \frac{M}{L_c L_r - M^2} \frac{U_{1m}}{\omega} \sin\left(\omega t - \frac{\pi}{2}\right) \tag{18}$$

$$i_r = -\frac{M}{L_c L_r - M^2} \frac{U_{1m}}{\omega} \cos \omega t \tag{19}$$

The inductance of the coil (L_c) and the inductance of the ring (L_r) were assumed as constant. In fact, after the coil is fired, the core inside the coil is saturated and both inductances drop rapidly to a constant value. In order to find out the magnetic flux density inside the air gap (B_g), the following assumption should be made:

1) The magnetic flux density inside the air gap is uniformly distributed;

2) No fringe flux at the end of the air gap.

$$R_c i_c - u_1 = -L_c \frac{di_c}{dt} + M\frac{di_r}{dt} \tag{20}$$

Because the $R_c = 0$ assumption it is still valid:

$$u_1 = N\frac{d\varphi_c}{dt} - N\frac{d\varphi_r}{dt} \tag{21}$$

$$u_1 = N\left(\frac{d\varphi_c}{dt} - \frac{d\varphi_r}{dt}\right) \tag{22}$$

$$\frac{d\varphi_c}{dt} - \frac{d\varphi_r}{dt} = \frac{d\varphi_1}{dt} \tag{23}$$

$$u_1 = N\frac{d\varphi_1}{dt} \tag{24}$$

$$\varphi_1 = \int d\varphi_1 = \int \frac{U_{1m}}{N} \sin \omega t\, dt \tag{25}$$

$$\varphi_1 = -\frac{U_{1m}}{N\omega} \sin\left(\omega t - \frac{\pi}{2}\right) \tag{26}$$

$$\varphi_1 = -\frac{U_{1m}}{N\omega} \cos \omega t \tag{27}$$

All the magnetic flux lines are split into two by the columns, and the magnetic flux density inside one air gap becomes:

$$\frac{\varphi_1}{2} = B_g A_g \tag{28}$$

$$B_g = \frac{\varphi_1}{2A_g} = \frac{\varphi_1}{2\frac{\pi r}{2} h_E} \tag{29}$$

$$B_g = -\frac{U_{1m}}{N\omega\pi r h_E} \cos \omega t \tag{30}$$

From equations 4, 19, 30 and because the ring has two parts inside air gaps, the total Lorentz force acting on ring is:

$$F = 2F_g \tag{31}$$

$$F = 2\frac{\pi r}{2}\left(-\frac{M}{L_c L_r - M^2}\frac{U_{1m}}{\omega}\cos \omega t\right) \cdot \left(-\frac{U_{1m}}{N\omega\pi r h_E}\cos \omega t\right) \tag{32}$$

$$F = \frac{M}{L_c L_r - M^2} \frac{U^2{}_{1m}}{N h_E \omega^2} \cos^2 \omega t \tag{33}$$

$$F = \frac{M}{L_c L_r - M^2} \frac{N}{h_E} \Phi_{1m}^2 \cos^2 \omega t \tag{34}$$

But the mutual inductance M depends on the distance between the coil and the ring, and the dimensions of the coil and ring. By changing these dimensions, the mutual inductance will change. As a result, mutual inductance M can be expressed as a function of coupling coefficient k where $0 \le k < 1$.

$$M = k\sqrt{L_c L_r} \qquad (35)$$

The equation of Lorentz force acting on ring becomes:

$$F = \frac{k\sqrt{L_c L_r}}{L_c L_r - k^2 L_c L_r} \frac{N}{h_E} \Phi_{1m}^2 \cos^2 \omega t \qquad (36)$$

$$F = \frac{k}{1-k^2 1_r} \frac{N}{h_E \sqrt{L_c L_r}} \Phi_{1m}^2 \cos^2 \omega t \qquad (37)$$

This expression of force is a good approximation when based on assumptions made.

3. SIMULATION

In order to test the theoretical results, I have used an interactive software package based on the finite element method (FEM) to analyze, solve three-dimensional electro-magnetic field problems and simulate E-shaped design's behaviors. First, I built a physical model with the same dimensions already presented. I conducted a lot of experiments in order to determine the behavior of this device. After that, I created a computer model calibrated to reproduce the behavior of the physical model with errors below 1%.

In this section only the results of the simulation will be presented. The main objective of all simulation was to establish how the maximum speed of ring varies based on the ring's mass and the source voltage. The mass of the ring was considered the mass of the entire ensemble of ring-UAV and the drag forces caused by air friction were not taken into consideration. In order to obtain the maximum force, the coil is fired in all the simulations at 180 degrees. The results of these simulations are presented in the following graphs. First the behavior of the "E-shaped" device was simulated under laboratory conditions like the physical model.

1) The flux linkage and force are simulated under the same conditions like the physical model in laboratory.

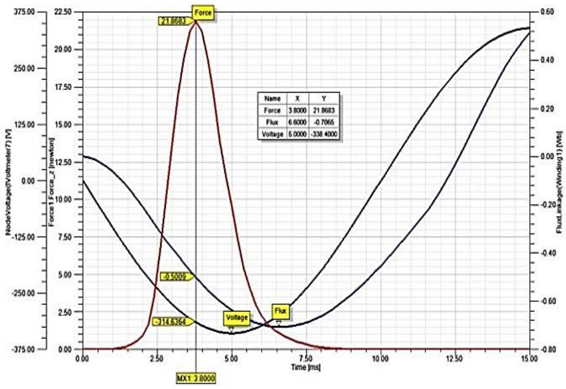

Fig.3 Force and flux linkage under laboratory conditions

The force achieves the maximum value F=21.86 N at 3.8 ms because the ring starts to move and, as a result, the coupling coefficient is decreases in value. Linkage flux lags behind the voltage with 28.8 degrees. The minimum value of the flux is $\Phi_1 = -0.7066\,\mathrm{Wb}$ but the force achieves its maximum at $\Phi_1 = -0.5009\,\mathrm{Wb}$. Not all the energy is used to create force. If the ring is kept in place for 2.8 more ms, the entire available energy will be used. These data will be used for comparison purposes with further simulation data. By increasing the mass of the ring the force acting on the ring will increase but the speed of ring will decrease.

2) The variation of the Lorentz force when the mass of the ring varies with values from 5 to 100 with step 5 grams and from 100 to 400 with step 100 grams.

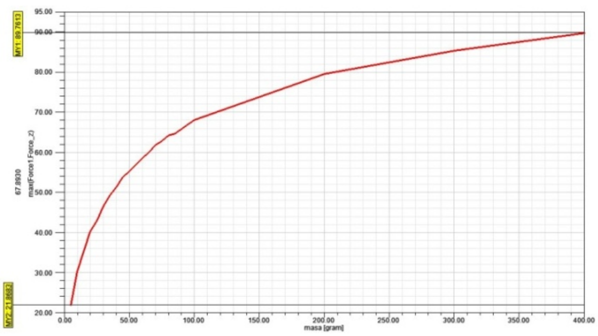

Fig.4 The variation of the maximum value of the Lorentz force [N] for different values of the ring mass

Because the mass of the ring is increased the time when the ring remains into the most favorable position (close to coil) is also increased and as a result the force is increased up to the point where the flux linkage achieves its minimum in our case.

The variation of the ring speed when the mass of the ring varies with values from 5 to 100 with step 5 grams and from 1to 400 with step 100 grams. According to Fig. 5 graph, even if the force is increased, the muzzle speed of the ring decreases. In order to increase the speed of ring, the mass of the ring is kept constant (10 grams) and the RMS value of source voltage is increased with values from 120 to 1200 V with step 120 V.

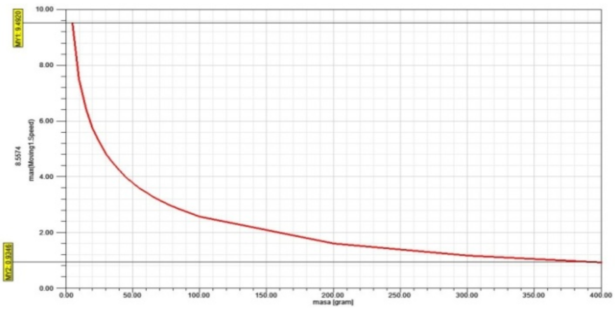

Fig.5 The variation of the maximum value of ring speed [m/s] for different values of ring mass

3) The variation of the ring speed for a variation of source voltage.

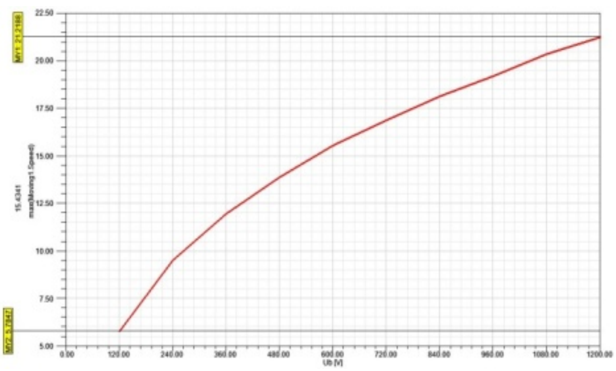

Fig.6 Ring speed variation [m/s] for different RMS values voltage [V]

When the voltage is increased 10 times the speed of the ring is increased only 3.66 times. The reason for this behavior will be clear if we study the variation in time of force with power voltage. The next graph displays this variation.

4) The time variation of force for different RMS values of voltage.

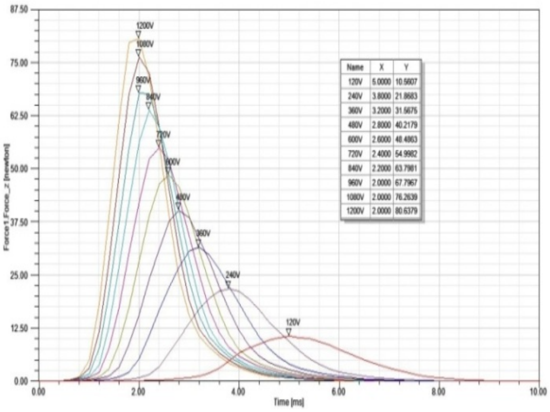

Fig.7 Force acting on the ring function of time

When the voltage value is increased 10 times, the force value is increased 7.63 times. The moment of time when the force achieves its maximum decrease, from 5 ms to 2 ms, and this means that not all the available energy is used. If the power voltage increases more and more, the device will be less efficient despite the fact that the force will increase. In order to find out the maximum value of the force for a certain available energy, we should keep the ring static.

5) The force variation for different RMS values of voltage when the ring is kept static.

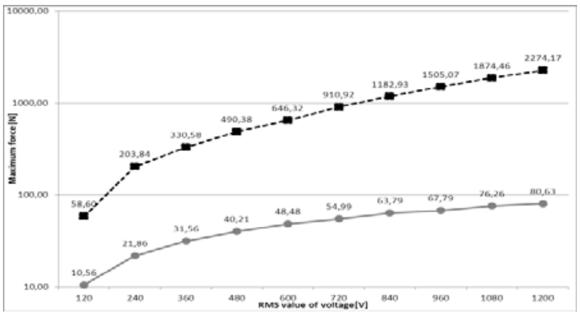

Fig.8 The maximum force acting on the ring

If we manage to keep the ring in initial position until the linkage flux achieves its minimum, then the force acting on the ring will be a maximum value and, as a result, the speed will be at maximum value. Fig. 8 displays a comparison between the maximum force acting on the ring when the ring can move freely (gray chart) and the maximum force acting on the ring, when the ring is static (black chart). The vertical axis is logarithmic base 10. But maybe even under these conditions the force is not strong enough to launch an UAV. The force value can be increased by reducing the electrical resistance of the coil and ring. In the theory section of this paper the equation of force was calculated when $R_c = 0$ and $R_r = 0$. The next graph displays the results of a simulation with $R_c = 0$ and $R_r = 0$ when the ring is kept static in order to find the maximum value of force for a certain value of power voltage (in this case RMS 240V). The variation of force with $R_c = 0$ and $R_r = 0$ for U_1=240V.

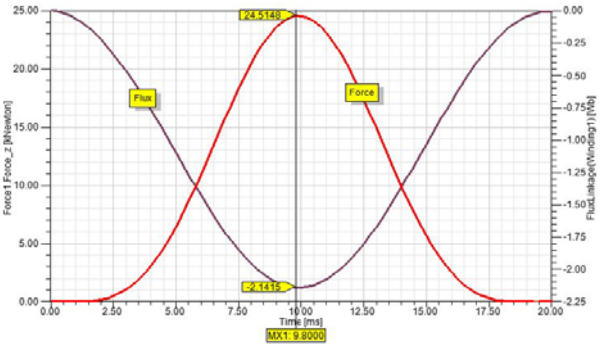

Fig.9 Force and flux linkage when $R_c = 0$ and $R_r = 0$

A tremendous increase in the force value is obtained under these conditions. Also, the flux lags behind the voltage with approximately $\pi/2$ radians according to theory. If the electrical resistance of the coil and ring is reduced to zero, which is technically possible, the maximum force generated can be F=24.5148 kN. So, instead of increasing the voltage, a more efficient way is to reduce the electrical resistance of the coil and ring.

3. CONCLUSIONS

The “E-shaped” design is capable to generate a force strong enough to launch a UAV. Also, the force can be adapted based on the UAV mass and launch speed, and as a result one catapult can be used for different UAVs. An electrical source of power is already available to power other equipment for communication and control link and can be used to power this catapult. This kind of catapult can be integrated into automatic control loop. The dimensions of this catapult are less than those of the catapult currently used. Further research should be made although the electromagnetic launch systems have proved their capability to accelerate projectiles at high speeds.

BIBLIOGRAPHY

1. Balicki, A., Zabar, Z., Birenbaum, L & Czarkowski, D. (2007). On the design of coilguns for super-velocity launchers. *IEEE Trans. on Magnetics*, vol. 43, no. 1. 107-110.
2. Fair, H.D. (2007). Progress in electromagnetic launch science and technology. *IEEE Trans. on Magnetics*, vol. 43, no. 1. 93-98.
3. Ghassemi, M., Molayi Barsi, Y., Hamedi, M.H. (2007). Analysis of force distribution acting upon the rails and the armature and prediction of velocity with time in an electromagnetic launcher with new method. *IEEE Trans. on Magnetics*, vol. 43, no. 1.
4. Gherman, L., Pearsică, M., Strîmbu, C. & Constantinescu, C.-G. (2011). Induction coilgun based on “E-shaped” design. *IEEE Trans. on Plasma Science*, vol.39, no. 2. 725-729.
5. McNab, I.R. & Beach, F.C. (2007). Naval railguns. *IEEE Trans. on Magnetics*, vol. 43, no. 1. 463-468.
6. ***. (2011). Railgun [online]. *Wikipedia*. URL: http://en.wikipedia.org/wiki/Railgun. [consulted on September 20, 2011).