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Two fluxes multistage induction coilgun

L Gherman[1], M Pearsica[1], I Circiu[2] and C Rotaru[2]

[1]"Henri Coandă" Air Force Academy, Air Defense Department, Mihai Viteazul str., no. 160, 500183 Brasov, Romania
[2]"Henri Coandă" Air Force Academy, Aviation Department, Mihai Viteazul str., no. 160, 500183 Brasov, Romania

E-mail: lauriang@gmail.com

Abstract. This paper presents a brand new induction electromagnetic launcher, which uses two magnetic fluxes in order to accelerate a projectile. One magnetic flux induce a current in the armature and the second magnetic flux is creating a radial magnetic field. This aproach offer multiple advantages over single flux designs. First we are able to control the induced current in armature because we use the coil just to induce current inside the ring with a great efficiency. Second advantage is the angle of 90^0 between magnetic field density B and the ring. We used the induction to avoid contact between armature and accelerator. In order to create the magnetic field radial we used four coils perpendicular on armature. This approach alove us to control the phase difference between induced current in armature and current in magnetic field coils for a maximum force. The phase difference is obtained by changing the frequency of magnetic field coils power source. We used simulation software to analyze, and simulate a multistage induction coilgun design with two fluxes. The simulation results demonstrated the theoretical results.

1. Introduction

The actual guns to accelerate projectiles based on chemical energy have achieved their limits but the requirements are continuously growing. The electromagnetic launch systems (EMLS) can expand the possibilities of guns [1], [2].

Many EMLS are designed to use the Lorentz force

$$\vec{F} = I \int d\vec{l} \times \vec{B} \tag{1}$$

A well-known design is railgun. The railgun consists of two rails and an armature made by conducting material. The armature is connected with both rails and is accelerated alongside the rails. The armature is accelerated by Lorentz force alongside the rails when the rails are powered by a high current.

In the railgun (Figure 1) the current I is the same current provided by the power system. The rail creates the magnetic field $\vec{B}$.

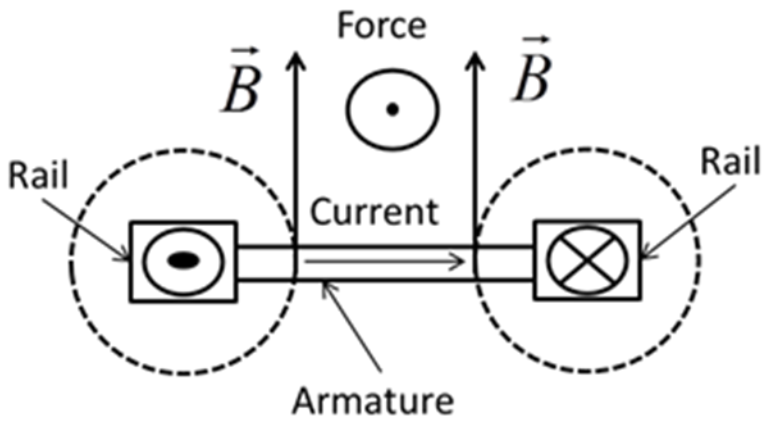

Figure 1. Railgun

A high value of the force is obtained when is used a very high value of current *I* and, therefore, a big power supply system.

Because of this high currents used those electric contacts affect the rails during lunches [3]. In order to reduce the value of current *I* the rails can be replaced by coils.

The current inside armature is obtained by using induction instead of sliding contacts.

$$u_i = -\frac{d\Phi_B}{dt} \tag{2}$$

$$u_i = -\frac{d}{dt}(BA\cos\theta) = -\left(\frac{dB}{dt}\right)A\cos\theta - B\left(\frac{dA}{dt}\right)\cos\theta + BA\sin\theta\left(\frac{d\theta}{dt}\right) \tag{3}$$

where θ is the angle between $\vec{B}$ and $\vec{n}$ (normal unit of surface area A). We assume the magnetic field is uniform distributed in space.

The coilgun design is based on induction where only the magnetic field is variable, the surface *A* and angle θ are constant. The Faraday's law can be writhed:

$$u_i = -\left(\frac{dB}{dt}\right)A\cos\theta \tag{4}$$

One approach consists of a barrel of coils which allow a projectile made by aluminium to move inside them [4]. The magnetic flux created by the coils is the only one magnetic flux, which induces current in projectile and provides the radial magnetic field which interacts with the induced current. It is difficult to control in the same time with one coil the rate of change of the axial magnetic density $\overrightarrow{B_a}$ and the radial magnetic flux density $\overrightarrow{B_r}$ [5]. In order to increase the radial magnetic flux density $\overrightarrow{B_r}$ a design with magnetic circuit made by ferromagnetic materials was proposed (Figure 2).

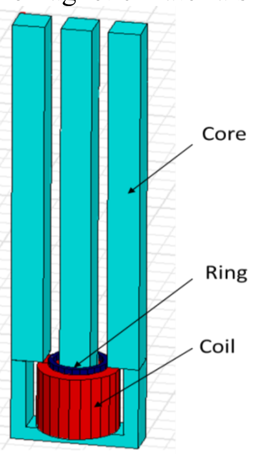

Figure 2. E shaped coilgun [6]

The E shaped design create a magnetic circuit but does not allow to control the difference of phase between induced current in projectile and the phase of the radial magnetic flux density $\overrightarrow{B_r}$.

Based on this observation we can identify the main aspects which should be taken into consideration when an electromagnetic launch system is designed. First the Lorentz force should be used to accelerate the projectile. Second the contact between the projectile and the accelerator should be avoided. Because of this, coils should be used to induce current into projectile. By using induction the value of current I induced into armature can be higher than the current provided by the power system.

Third the design should give us the possibility to change the phase of induced current in armature and the phase of the radial magnetic flux density$\overrightarrow{B_r}$ in order to obtain a high value of the Lorentz force. A coilgun, which obeys all this conditions, is presented in the following section.

2. A multistage induction coilgun design with two fluxes

First we calculate an air core coil which will induce current into a ring placed outside (Figure 3). The aluminium ring is placed outside solenoid because it will act as armature, which will be mechanical coupled with projectile.

$$u_i = -\left(\frac{dB}{dt}\right) A \cos\theta = -\left(\frac{dB}{dt}\right) A \tag{5}$$

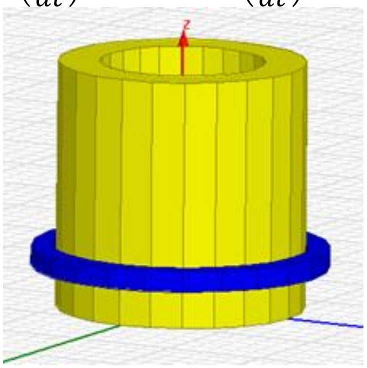

Figure 3. The induction coil

We need another coil, which will create the radial magnetic field [4]. Usually the armature in a coilgun is placed inside the coil and the current I and magnetic field B are produced by the same coil. For our design the magnetic field B is produced by others air core coils placed around ring at θ=90^0 in order to obtain maximum force on the ring (Figure 4).

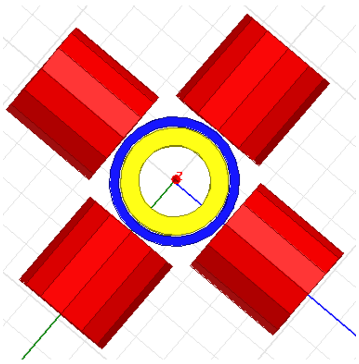

Figure 4. The magnetic field coils around ring at θ=90^0

All coils (induction and magnetic field) have the same dimensions in order to have the same resistance R and the same inductance L. Because the armature (ring) will be accelerated using multiple stages this design give us the possibility to create multiple stages (Figure 5).

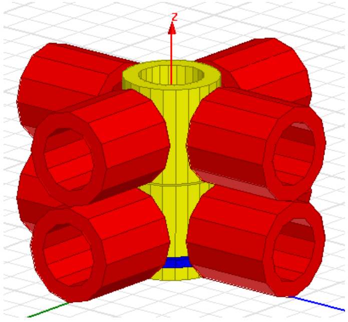

Figure 5. EMLS with 2 stages of acceleration

The simplified drawing of this circuit is displaied in Figure 6. We chose to represent only the induction coil Lb, the ring Li and the coil which produce the magnetic field Lc.

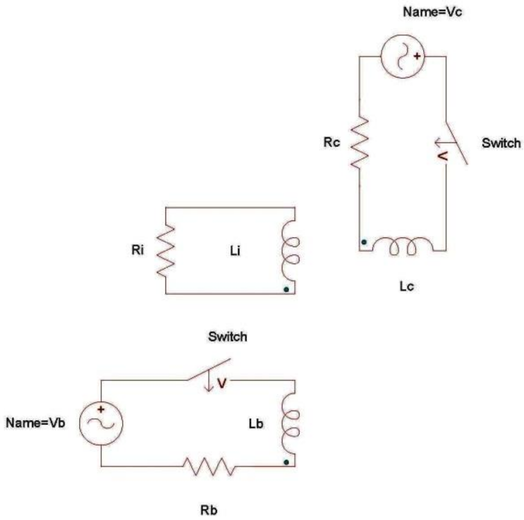

Figure 6. Drawing of electrical circuit

The ring is a short circuit but the coils are powered by two sinusoidal sources with following expression.

$$U_b = U_{bmax}\sin(\omega_1 t + \alpha) \tag{6}$$
$$U_c = U_{cmax}\sin(\omega_2 t + \beta) \tag{7}$$

Because all coils are identical we have the following equality:

$$L_b = L_c \text{ and } R_b = R_c$$

Applying the KVL we obtain the following system of differential equations:

$$\begin{cases} U_b = Ri_b + L\dfrac{di_b}{dt} - M_{bi}\dfrac{di_i}{dt} - M_{bc}\dfrac{di_c}{dt} \\ 0 = R_i i_i + L_i\dfrac{di_i}{dt} - M_{bi}\dfrac{di_b}{dt} - M_{ci}\dfrac{di_c}{dt} \\ U_c = Ri_c + L\dfrac{di_c}{dt} - M_{ci}\dfrac{di_i}{dt} - M_{bc}\dfrac{di_b}{dt} \end{cases} \tag{8}$$

$$\begin{cases} U_b + M_{bi}\dfrac{di_i}{dt} + M_{bc}\dfrac{di_c}{dt} = Ri_b + L\dfrac{di_b}{dt} = V_b \\ M_{bi}\dfrac{di_b}{dt} + M_{ci}\dfrac{di_c}{dt} = R_i i_i + L_i\dfrac{di_i}{dt} = V_i \\ U_c + M_{ci}\dfrac{di_i}{dt} + M_{bc}\dfrac{di_b}{dt} = Ri_c + L\dfrac{di_c}{dt} = V_c \end{cases} \tag{9}$$

$$\begin{cases} V_b = Ri_b + L\dfrac{di_b}{dt} \\ V_i = R_i i_i + L_i\dfrac{di_i}{dt} \\ V_c = Ri_c + L\dfrac{di_c}{dt} \end{cases} \tag{10}$$

The expressions of currents are:

$$\begin{cases} i_b = I_{bmax}\sin(\omega_b t + \gamma) + I_{bmax}\sin(\gamma)e^{-\frac{R}{X}\omega_b t} \\ i_i = I_{imax}\sin(\omega_i t + \lambda) + I_{imax}\sin(\lambda)e^{-\frac{R_i}{X_i}\omega_i t} \\ i_c = I_{cmax}\sin(\omega_c t + \varepsilon) + I_{cmax}\sin(\varepsilon)e^{-\frac{R}{X}\omega_c t} \end{cases} \tag{11}$$

Because the time when the ring is accelerated on a stage is very short (below 10 ms) the Lorentz force acting on ring depend only by the first semi period current oscillation at 50 Hz.

The expression of currents can be approximated:

$$\begin{cases} i_b = I_{bmax}\sin(\omega_b t + \gamma) + I_{bmax}\sin(\gamma) \\ i_i = I_{imax}\sin(\omega_i t + \lambda) + I_{imax}\sin(\lambda) \\ i_c = I_{cmax}\sin(\omega_c t + \varepsilon) + I_{cmax}\sin(\varepsilon) \end{cases} \tag{12}$$

The magnetic field created by the L_c solenoid can be calculated according with Ampere's law:

$$\oint B \cdot dl = \mu_0 i_{enclosed} \tag{13}$$

In our case $i_{enclosed}=i_c$ and the expression of B at the end of solenoid L_c became:

$$B = \mu_0 \frac{N}{2\sqrt{r^2 + h^2}} i_c \tag{14}$$

where:
N=number of turns of solenoid (dimensionless);
r = radius of coil (meters);
h = length of solenoid (meters).
The expression of Lorentz force became:

$$F = l \cdot B_c \cdot i_i = l \cdot \mu_0 \frac{N}{2\sqrt{r^2 + h^2}} i_c \cdot i_i \tag{15}$$

$$F = l \cdot \mu_0 \frac{N}{2\sqrt{r^2 + h^2}}[I_{cmax}\sin(\omega_c t + \varepsilon) + I_{cmax}\sin(\varepsilon)] \cdot [I_{imax}\sin(\omega_i t + \lambda) + I_{imax}\sin(\lambda)]$$

$$F = l \cdot \mu_0 \frac{N}{2\sqrt{r^2+h^2}} I_{cmax} I_{imax}[\sin(\omega_c t + \varepsilon) + \sin(\varepsilon)] \cdot [\sin(\omega_i t + \lambda) + \sin(\lambda)] \tag{16}$$

In order to find the maximum value of Lorentz force F we should find the maximum of expression:

$$max[\sin(\omega_c t + \varepsilon) + \sin(\varepsilon)] \cdot [\sin(\omega_i t + \lambda) + \sin(\lambda)] \tag{17}$$

$$[\sin(\omega_c t + \varepsilon) + \sin(\varepsilon)] \cdot [\sin(\omega_i t + \lambda) + \sin(\lambda)] = \frac{1}{2}[\cos(\lambda - \varepsilon) - \cos(\lambda + \varepsilon)](cos\omega_i t + 1)(cos\omega_c t + 1) + \frac{1}{2}[\cos(\lambda - \varepsilon) + \cos(\lambda + \varepsilon)]\sin(\omega_i t)\sin(\omega_c t) + \frac{1}{2}[\sin(\lambda - \varepsilon) + \sin(\lambda + \varepsilon)](cos\omega_i t + 1)\sin(\omega_c t) + \frac{1}{2}[\sin(\lambda + \varepsilon) - \sin(\lambda - \varepsilon)](cos\omega_c t + 1)\sin(\omega_i t) \tag{18}$$

Because the above expression does not have a global maximum we maximize each expression of the sum. We obtain the following situation:

I. $$max[\cos(\lambda - \varepsilon) - \cos(\lambda + \varepsilon)] = 2 \tag{19}$$

When $(\lambda - \varepsilon) = 0$ and $(\lambda + \varepsilon) = \pi$ where $\lambda = \varepsilon = \frac{\pi}{2}$

The expression becomes:

$$(cos\omega_i t + 1)(cos\omega_c t + 1) \tag{20}$$

And the maximum of:

$$max(cos\omega_i t + 1)(cos\omega_c t + 1) = 4 \tag{21}$$

when $\omega_i = \omega_c = 2\pi f$

I. $$max[\cos(\lambda - \varepsilon) + \cos(\lambda + \varepsilon)] = 2 \tag{22}$$

when $(\lambda - \varepsilon) = 0$ and $(\lambda + \varepsilon) = 0$ where $\lambda = \varepsilon = 0$

The expression becomes:

$$\sin(\omega_i t)\sin(\omega_c t) \tag{23}$$

And the maximum of:

$$max\,\sin(\omega_i t)\sin(\omega_c t) = 1 \tag{24}$$

when $\omega_i = \omega_c = 2\pi f - \frac{\pi}{2}$

$\omega_i = \omega_c = 2\pi f + \frac{\pi}{2}$

II. $$max[\sin(\lambda - \varepsilon) + \sin(\lambda + \varepsilon)] = 2 \tag{25}$$

when $(\lambda - \varepsilon) = \frac{\pi}{2}$ and $(\lambda + \varepsilon) = \frac{\pi}{2}$

where $\lambda = \frac{\pi}{2}$ $\varepsilon = 0$

The expression becomes:

$$(cos\omega_i t + 1)\sin(\omega_c t) \tag{26}$$

And the maximum of:

$$max(cos\omega_i t + 1)\sin(\omega_c t) = 2 \tag{27}$$

when $\omega_i = 2\pi f + \pi$ $\omega_c = 2\pi f - \frac{\pi}{2}$

IV. $$max[\sin(\lambda + \varepsilon) - \sin(\lambda - \varepsilon)] = 2 \tag{28}$$

when $(\lambda - \varepsilon) = -\frac{\pi}{2}$ and $(\lambda + \varepsilon) = \frac{\pi}{2}$

where $\lambda = 0$ $\varepsilon = \frac{\pi}{2}$

The expression becomes:

$$(cos\omega_c t + 1)\sin(\omega_i t) \tag{29}$$

And the maximum of:

$$max(cos\omega_c t + 1)\sin(\omega_i t) = 2 \tag{30}$$

when $\omega_c = 2\pi f + \pi$ $\omega_i = 2\pi f - \frac{\pi}{2}$

Because λ and ε represent the phase delay of induced current i_i and magnetic field coil current i_c we should analyse all four situations.

First situation is obtained when $\lambda = \varepsilon = \frac{\pi}{2}$ but it is very difficult to obtain the same phase for induced current and current inside magnetic field coils because of mutual induction between coils. The expression of force becomes:

$$F = F_{Imax}(cos\omega_i t + 1)(cos\omega_c t + 1) \tag{31}$$

Second situation is obtained when $\lambda = \varepsilon = 0$ also very difficult to obtain with coils. The expression of force becomes:

$$\mathrm{F} = F_{IImax}\sin(\omega_i t)\sin(\omega_c t) \tag{32}$$

Third situation is obtained when $\lambda = \frac{\pi}{2}$ $\varepsilon = 0$.

The expression of force becomes:

$$F = F_{IIImax}(cos\omega_i t + 1)\sin(\omega_c t) \tag{33}$$

Last situation is obtained when $\lambda = 0$ $\varepsilon = \frac{\pi}{2}$. The expression of force becomes:

$$F = F_{IVmax}(cos\omega_c t + 1)\sin(\omega_i t) \tag{34}$$

In third and fourth case, we create condition to achieve a certain delay between phases of induced current in ring and magnetic field coil current.

Theoretically the maximum of Lorentz force F is obtained in first case when $\lambda = \varepsilon = \frac{\pi}{2}$ and $\omega_i = 2\pi f_i$ and $\omega_c = 2\pi f_c$. Practically the maximum of Lorentz force F is obtained in third and fourth case when $\lambda = \frac{\pi}{2}\,\varepsilon = 0$ or $\lambda = 0$ $\varepsilon = \frac{\pi}{2}$ and $\omega_i = 2\pi f + \pi$ $\omega_c = 2\pi f - \frac{\pi}{2}$

For these conditions the expression of Lorentz force became:

$$F = 2l \cdot \mu_0 \frac{N}{2\sqrt{r^2+h^2}} I_{cmax} I_{imax} = l \cdot \mu_0 \frac{N}{\sqrt{r^2+h^2}} I_{cmax} I_{imax} \quad (35)$$

Because we approximated the expression of currents for ideal conditions it is not possible to obtain the same values for phase but we are looking for a maximum value of force between those values.

The following dimensions of this design were calculated [5]. The mass of aluminium ring was calculated at 10 grams. We started from dimensions of device used for E shaped.

Table 1. Coil parameters

	Induction coil	Magnetic field coil	Ring
Inner radius	20 mm	20 mm	31 mm
Outer radius	30 mm	30 mm	36 mm
Length	60 mm	60 mm	5 mm
Number of turns	300	300	1

The Maxwell interactive software package that uses the finite element method (FEM) was used to analyse, and simulate two fluxes multistage induction coilgun design [7], [8].

3. The results of simulation

The coilgun with these dimensions was created using 3D simulation software. The values of voltages and duration of pulses for every stage are presented in Table 2. In this simulation all coils from the same stage were powered with the same voltage.

Table 2. Stages parameters

	Stage 1	Stage 2
Voltage RMS	700V	1400V
Time	6.6 ms	0.7 ms

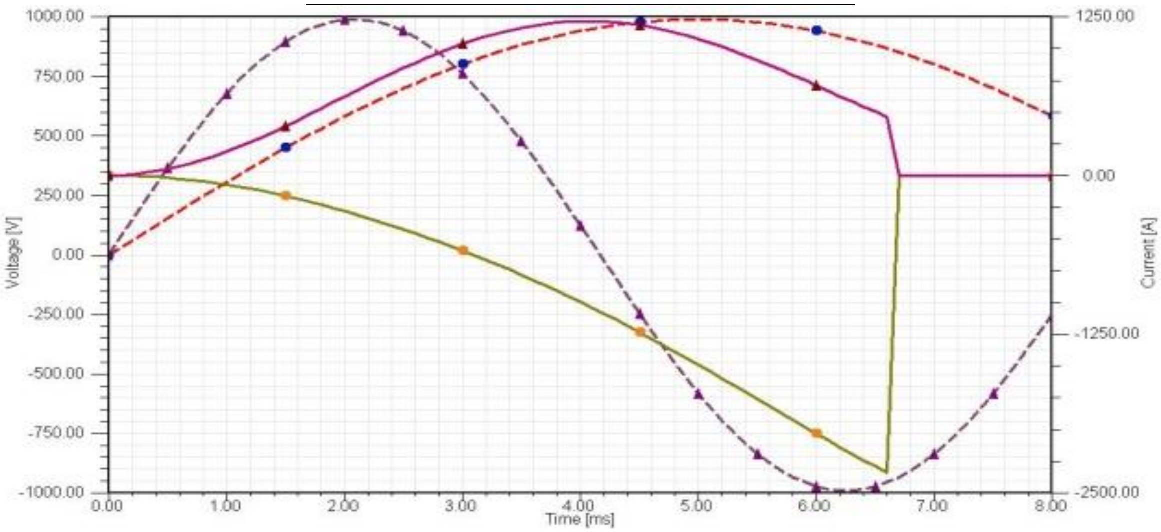

Figure 7. Stage 1 power voltage and current

In Figure 7 is presented the time variation of voltage and current in stage 1 coils. With long dash and circle is presented the time variation of voltage source, which power the induction coil. The frequency is 50 Hz and the phase is zero. The continuous line with circle is the time variation of the current inside the induction coil. With long dash and triangle is presented the time variation of voltage source which power the magnetic field coil. In order to obtain the maximum Lorentz force the frequency of power source of magnetic field coils was changed to 120 Hz with the same phase zero. The resistance of coil was decreased at a very low value in order to obtain the phase 90^0 for current. The continuous line with triangle is the time variation of the current inside the magnetic field coil. At 6.6 ms when the ring left the stage 1 the power line is switched off and the value of currents inside stage 1 coils drop rapidly to zero value.

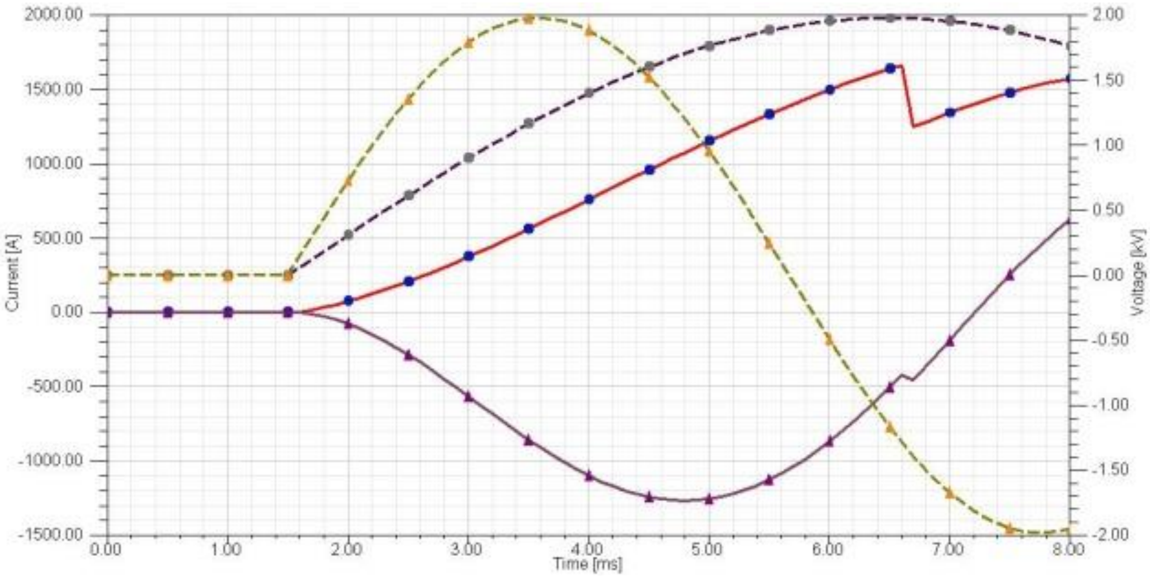

Figure 8. Stage 2 power voltage and current

In Figure 8 is presented the time variation of voltage and current in stage 2 coils. The power for stage 2 coils is switched on at 1.5 ms after first stage is powered in order to create a higher force when the ring arrive al second stage. With long dash and circle is presented the time variation of voltage source, which power the second stage induction coil. The frequency is 50 Hz and the phase is zero. The continuous line with circle is the time variation of the current inside the second stage induction coil. With long dash and triangle is presented the time variation of voltage source, which power the second stage magnetic field coil. The continuous line with triangle is the time variation of the current inside the second stage magnetic field coil. At 6.6 ms when the power line of first stage is switched off the value of currents inside stage 2 coils present a rapid variation. Because after the second stage the ring left the EMLS the power line was not switched off. For multiple stages, we should follow the same pattern.

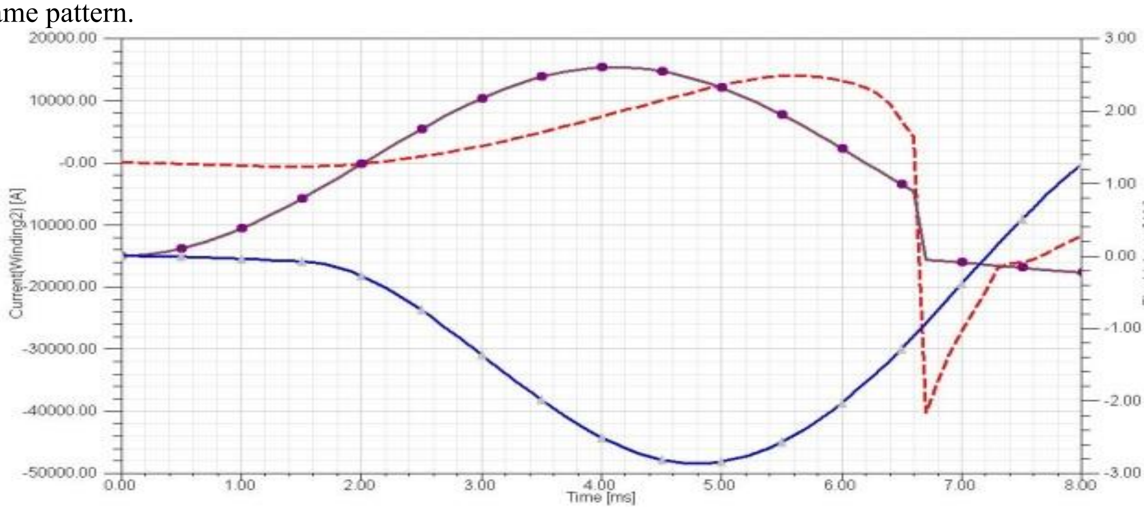

Figure 9. Time variation of induced current inside ring and flux linkage on both stages

The time variation of current induced into the ring is represented by long dash. The maximum value of induced in ring current is 13,973.6 A when the ring is in first stage and 40,236.2 A when the ring is in second stage. The maximum value of current used to induce the current into the ring is 2,332.9 A inside the induction coil from stage 1. All other coils are working with currents below this value. From this point of view, our design is better than the railgun because the value of current inside armature is higher than power supply current. The flux linkage created by stage 1 is presented using a continuous line with circle and for stage 2 is a continuous line with triangles.

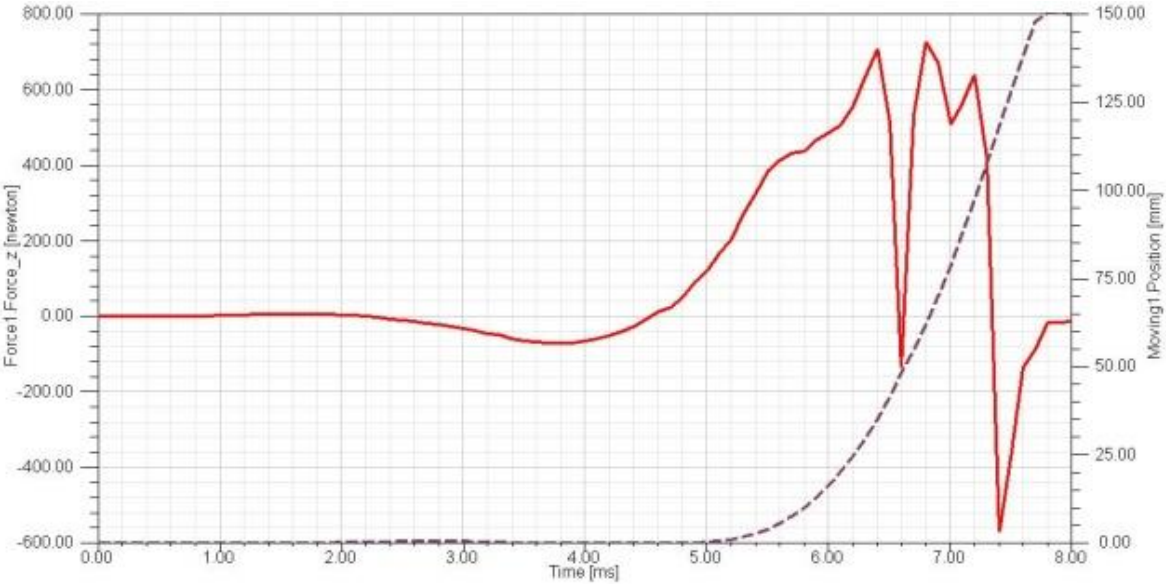

Figure 10. Time variation of Lorentz force and position of ring

In Figure 10 is presented with continuous line the time variation of Lorentz force which is accelerating the ring in Oz direction. The maximum value of force is 724.8 N. The force has a very rapid drop when the ring is passing from stage 1 to stage 2 and the power of stage 1 is switched off and after the ring left the EMLS. With long dash is presented the position of ring during acceleration time. The border between stages is at 40 mm and the limit of EMLS is at 101 mm.

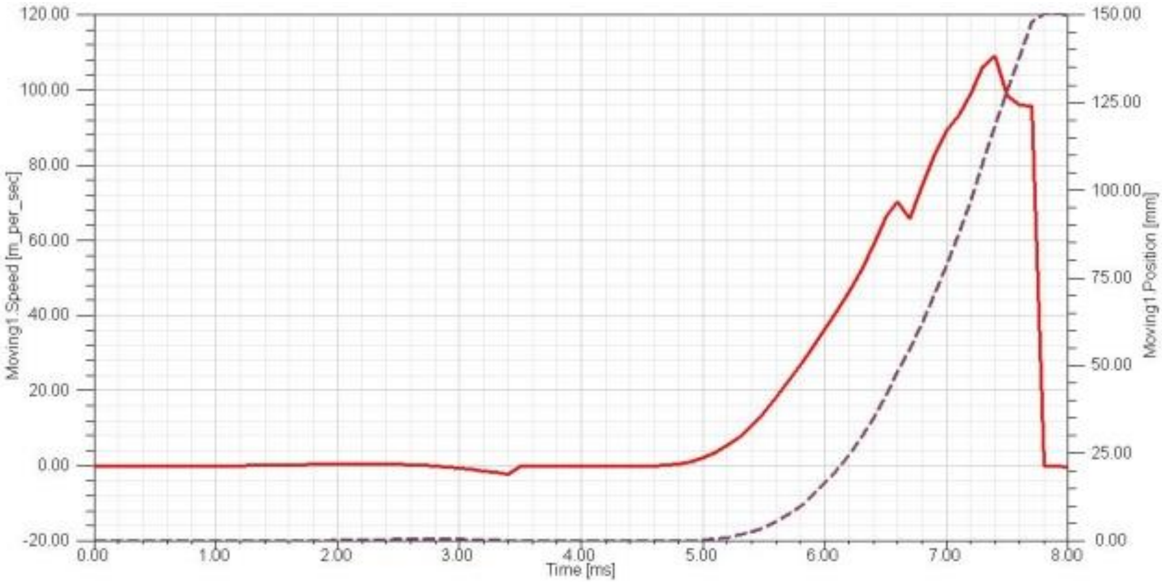

Figure 11. Time variation of speed of ring and position of ring

The time variation of speed of ring is presented with continuous line and with long dash is presented the position of ring during acceleration time. The ring left stage 1 at time 6.49 ms with speed 64.94 m/s and the stage 2 at time 7.23 ms with speed 101.96 m/s. The maximum speed 106.98 m/s is achieved at time 7.33 ms. After that time the ring is no longer accelerated and the speed drop rapidly to zero because the simulation length is 150 mm.

4. Conclusion

The multistage induction coilgun with two fluxes is better than single flux designs. The induced current in armature can be controlled much efficient because we use the coil just to induce current inside the ring with great efficiency. The magnetic field density B inside the air gap is perpendicular on ring and the Lorentz force accelerate the projectile during entire length of a stage.

We used the induction to avoid contact between armature and accelerator and to obtain a higher value of induced current than power current.

In order to create the radial magnetic field we used four coils perpendicular on armature. This approach give us the possibility to control the phase difference between induced current in armature and current in magnetic field coils in order to obtain the maximum force. The phase difference is obtained by changing the frequency of magnetic field coils power source. We do not need less electrical energy because is expensive but because we can use a small power source.

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