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ELECTROMAGNETIC COIL GUN – DESIGN AND CONSTRUCTION

ABSTRACT *A single-stage, sensor less, coil gun was designed to demonstrate the capability to accelerate a ferromagnetic projectile to high velocity. This paper summarize all important steps during coil gun design, such as physical laws of the coil gun, preliminary calculations, the testing device and final product.*

The electromagnetic FEA model of the capacitor-driven inductance coil gun was constructed to be able to optimize the coil's dimensions. The driving circuit was implemented as dynamic model for simulation of current.

The coil gun is designed for an exhibition centre as an exhibit. It is not designed for a really shooting applications, this means the projectile is accelerated at relatively low speed.

Keywords: *Coil gun, electronics, FEM, electromagnetic force*

1. INTRODUCTION

Electromagnetic accelerating systems are usually constructed as rail guns [3] or coil guns [1]. The rail gun is conceptually more simple than the coil gun, but has some inherent problems with plasma [2] during the projectile launches. That is why this conception is not use here.

On the other hand the coil gun is much more suitable for common applications even if it needs some additional supporting facilities [4] such as energy accumulator, switcher and driver. Its main advantage lies in loose of almost all negative phenomena damaging the launch device.

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Modern structures usually use single or multi-stage linear accelerator similar to linear motor. The device typically consists of an electromagnetic coil, capacitor, switch, barrel and movable core – projectile. The coil can be wound as a solenoid electromagnet with a ferromagnetic projectile placed at one of its ends (starting position).

The launching process can be divided into three phases. The situation can be reflected in Figure 1.

In the first phase the energy needed for acceleration is stored in the capacitor [1] C using laboratory direct current source U (switch position 1). In the following phase the energy must be transmitted to the projectile in the shortest possible time. The FET transistor working as a contactless switcher can be used for this purpose (switch position 2). This will provide a high-energy coil current peak creating a strong electromagnetic field. This field pulls the projectile inside the barrel with high acceleration.

For the successful projectile launch the precise timing is necessary [3]. The current pulse must be switched off before the projectile passes the half of the coil length to prevent the projectile from becoming arrested at the centre of the electromagnet. In the final, third stage, the projectile leaves the coil and flies on its own momentum.

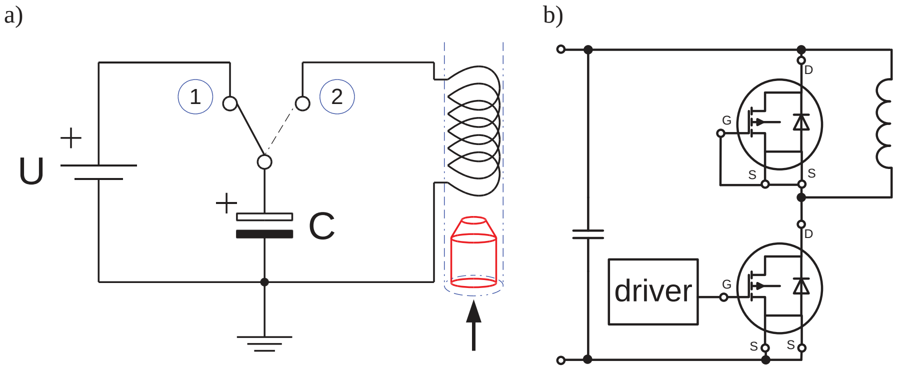


Fig. 1.
a) The principle of launching process, b) The power circuit connection (FET + diode + ejection coil)

2. MAIN COMPONENT DESIGN

2.1. The Projectile

As a projectile it was used 40mm long drilled iron cylinder with the outer diameter of 20 mm [3]. The upper side is threaded (M5) with penetration depth of 35 mm. This thread locks the screw with the Teflon casing (for leading string). Thanks to this material the friction is minimized as much as possible. The lower side of the projectile is made with similar (but Teflon less) casing as used in the top.

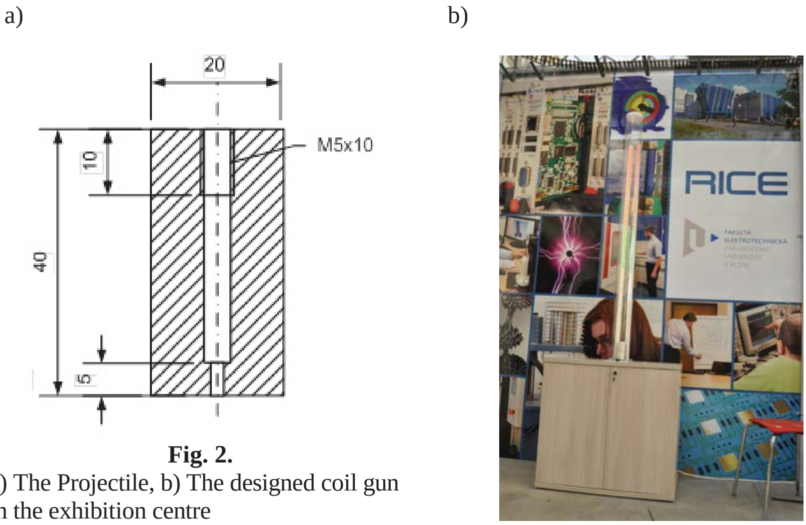


Fig. 2.
a) The Projectile, b) The designed coil gun in the exhibition centre

The volume of the projectile can be calculated as

$$V = \pi r^2 v = \pi\, 0{,}01^2 0{,}04 = 12{,}56 \cdot 10^{-6}\ \mathrm{m}^3 \qquad (1)$$

The iron volume density is ρ =7800 kg·m^3 and thus the projectile mass is

$$m = \rho V = 7800 \cdot 12{,}56 \cdot 10^{-6} = 0{,}098\ \mathrm{kg} \qquad (2)$$

This is valid for the projectile without drilled hole. The drilled projectile has a mass 0,0926 kg.

2.2. The Ejection Coil

The acceleration and speed characteristics of the projectile were computed. In order to get accurate results it was necessary to take into account in all calculations both; electrical and mechanical properties [3].

The mechanical properties are mainly defined by sizes of the muzzle of the coil gun.

The muzzle has a relatively large diameter, hence the inner air can easily flow around the projectile and the damping air pressure is at relatively low level. Based on the same reason the coil must be designed with the suction hole placed in the bottom part of the coil frame.

Finally, the electrical properties are strongly defined by the coil's resistivity and inductivity affecting the time constant of transient respond. The inductivity changes with the projectile position.

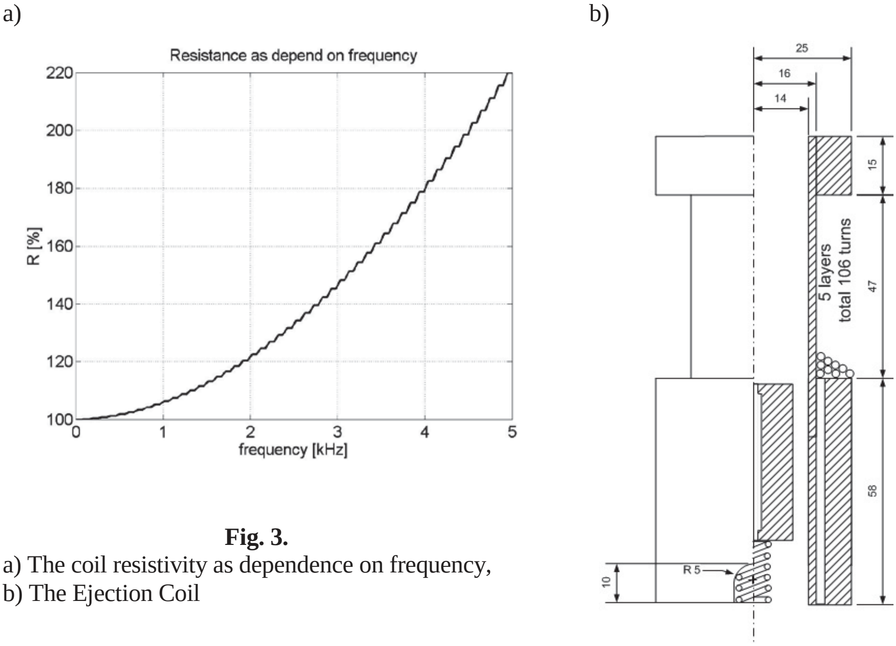


Fig. 3.
a) The coil resistivity as dependence on frequency,
b) The Ejection Coil

The resistivity depends on the frequency (skin and proximity effect) [6 – 7] of supplying current and cannot be therefore exactly computed by analytical equation. The curve computed by FEA can be seen in the Figure 3. The magnetic force depends on both the current and the position of the projectile with respect of the coil.

2.3. The Capacitors

The battery of fast electrolytic capacitors was used as a energy accumulator for a projectile shoot. As the voltage is a limiting parameter for all key components, the super-capacitor could not be utilized because of its voltage is still relatively low. Each of used capacitor provides discharging current of maximal value 30 A. The calculated coil gun current pulse is more than 350 A, due to this fact 10 capacitors in parallel connection were needed. The special sandwich board was developed and constructed.

The each capacitor has a capacity of 10 mF and nominal voltage 63 V. The total capacity is 0,1 F.

2.4. The Switching FET Transistor

The FET transistor of a nominal current of 340 A was chosen. The transistor package includes transistor and protective diode. The shooting cadence was set on one shot per 15-20 seconds and if the ejection pulse has duration about 15 ms there is no need of additional cooling of the transistor. In addition, the transistor was protected (voltage protection) by fast small capacitor.

2.5. The Supply Sources

The coil gun has several supply sources. The whole device is supplied from the common power grid. All sources are set up with input transformer.

Source No. 1. served for a charging the capacitor bank. The maximum voltage of this supply source is more than 50 V. The charging current is driven by integrated control circuit and the charging time is set to approximately 15 s.

Source No. 2 is designed for circuits of pulse shaper. The supply voltage is set to 13,2 V to prevent under voltage protection of FET transistor driver from behaving. Source No 3 supplied a LED bar-graph for indication of battery charging. The total consumption when all LEDs are luminous is 1,2 A.

2.6. The Control Circuit

The coil gun was designed as an exhibit for a children of a primary school and young students of secondary school. Due to this fact only one button was used for control. It starts the shooting sequence as follows:

1. charging the capacitor bank
2. the voltage of the capacitor bank is indicated by two bar-graphs
3. when the voltage of the capacitor bank reaches the pre-set value, the shaping circuit issue the order of a shoot automatically

The starting button activates the control bi-stable relay circuit charging the capacitors. This bi-stable circuit is retroactively deactivated with shooting pulse.

For the LED bar-graph control a special circuit was designed. The integrated circuit consist of 10 comparators where each comparator controls two elements of the bar-graph. The last comparator executes the pulse for a shooting generated by a mono stable circuit. The pulse has a length 120 ms. This time is enough for a bi-stable relay circuit deactivation and simultaneously for a total discharging of capacitors bank.

The last, the shaper circuit is a Schmidt trigger circuit with inverted output connected directly to the driver for the FET transistor.

2.7. The Driver of FET Transistor

The producer of this driver is YXIS company. The driver has an output current up to 30 A. This current is a maximum current flowing to a gate of a FET transistor. This pulse is very short and served for a charging of the gate only. Its length is independent on the time setting of the mono stable circuit.

There are several rules about placing the driver on a printed circuit board.

As close as possible to the terminals must be located three various capacitors:

- Electrolytic capacitor with extremely large capacity 33 mF. The conductive link (on the printed circuit) between this capacitor and driver terminals must be thickened by real wire or thinner;
- SMD capacitor 100 nF;
- Fast tantalum capacitor 10 μF.

Thanks to these three capacitors the voltage during the pulse does not decrease under the threshold of under voltage protection and FET transistor switches reliably without any oscillation.

3. THE EJECTION COIL MODEL

The electromagnetic field of the ejection coil was modelled in using FEM software. The coil were simulated in several versions. The best results we obtained in version with 5 wire layers, 21 turns per layer. The total number of turns is 106. The wire diameter is 2,000 mm.

The coil inductivity without any ferromagnetic material is 12,5 mH. With consideration of the ferromagnetic projectile centre of the coil, the inductivity is more than 2 times higher, i.e. 30,8 mH. This effect causes the serious problems – the coil has short time constant at the beginning and long time constant at the moment of switching off the current.

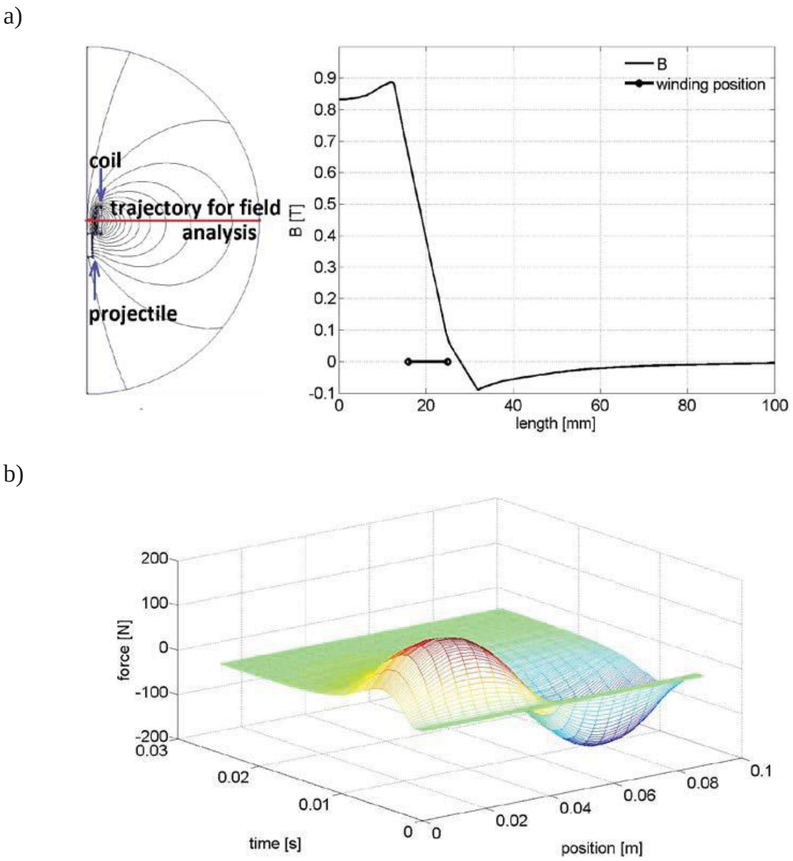
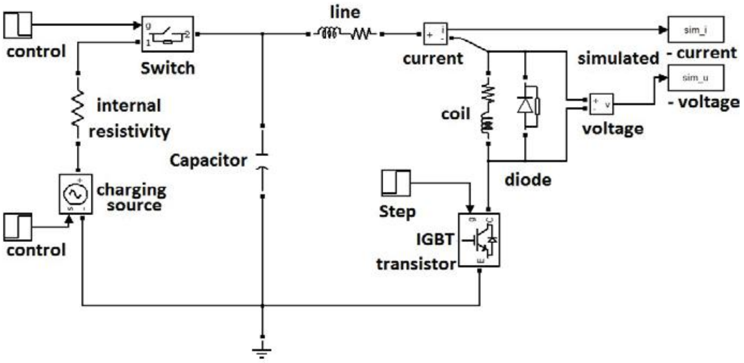


Fig. 4.
a) The field of the ejection coil I = 350 A - starting position; b) The matrix of the position and force of the ejection coil, the current is constant 350 A

4. THE ELECTRIC CIRCUIT SIMULATION AND MEASUREMENT

The basic electric circuit was simulated via MATLAB/SIMULINK see Figure 5. At the first moment, the capacitor charges from the control voltage source through the switcher (IGBTD switched off). After the charging process the switcher disconnects and the coil gun is ready to launch. When the IGBTD switches on, the current flows from the capacitor into the launching coil.

a)



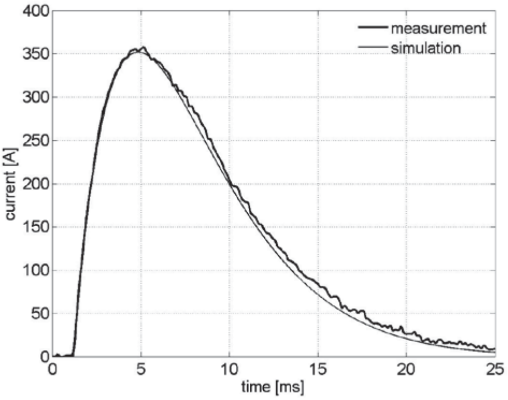
b)

Fig. 5.
a) The diagram of connection of power circuit; b) The construction of 2-layer sandwich

In the Figure 5a the component "line" represents the parameters of supplying cable. In Figure 5b, in the top, you can see the diode and FET transistor. In case of large parasite inductivity the enormous current causes the overvoltage and destroys the semiconductors. Due to this fact we have to design the “sandwich”. In addition, both semiconductors are static sensitive device.

In the following picture Figure 6 it can be seen the simulated and the measured coil's voltage and current.

a)



b)

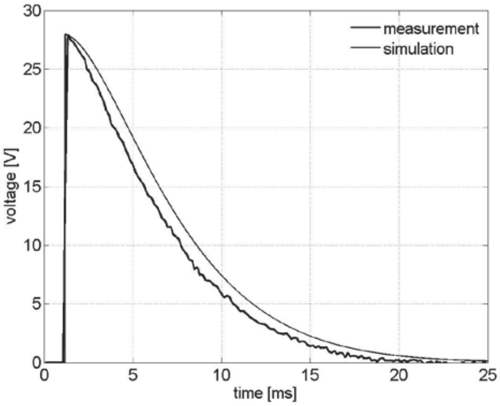


Fig. 6.
a) Measured and simulated coil's current; b) Measured and simulated coil's voltage

5. CONCLUSION

This paper has clearly shown the outline of construction of single-stage, sensor less, coil gun lunching system. It has also been demonstrated a few problems arising from strong coupling between electrical and mechanical properties of the coil. The findings of our research are quite convincing, and thus the following conclusions can be drawn:

The coil needs to be designed with respect to the varying time constant of transient respond. This must be considered from requested acceleration and output speed of the projectile (the current pulse must be down before the projectile passes the half of the coil length).

The high capacitor is needed for charging the energy. This capacitor must be implemented by special sandwich board (capacitors connected in parallel) because of proper discharging current distribution and overvoltage stress of the power electronics components.

Further research of the issue is still necessary to extend our knowledge about system's behaviour if the permanent magnet is used instead of the iron projectile.

ACKNOWLEDGEMENT

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LITERATURE

1. Dwight, H. B.: Proximity Effect in Wires and Thin Tubes, American Institute of Electrical Engineers, Transactions of the, vol. XLII, pp. 850-859, Jan. 1923.
2. Dwight, H.B.: Electrical coils and conductors, their electrical characteristics and theory, McGraw-Hill book company, inc., 1945.
3. http://www.ceskatelevize.cz/porady/10118379000-udalosti-v-regionech-praha/213411000140306-udalosti-v-regionech/video/247389 , valid March 12, 2013.
4. Kaye, R.J.: Operational requirements and issues for coilgun electromagnetic launchers, Magnetics, IEEE Transactions on, vol. 41, no 1, pp. 194-199, Jan. 2005.
5. Keshtkar, A.; Gharib, L.; Abbasi, M.: Comparison between conventional railgun and two-turn railgun by 3D- FEM, Electromagnetic Launch Technology (EML), 2012 16th International Symposium on, pp. 1-5, 15-19 May 2012
6. Liuming Guo; Ningning Guo; Shuhong Wang; Jie Qiu; Jian Guo Zhu; Youguang Guo; Yi Wang: Optimization for capacitor-driven coilgun based on equivalent circuit model and genetic algorithm, Energy Conversion Congress and Exposition, 2009. ECCE 2009. IEEE, pp. 234-239, 20-24 Sept. 2009
7. Yamori, A.; Ono, Y.; Sasaki, S.: Development of a plasma armature railgun with two distributed power supplies, Electromagnetic Launch Technology, 2004 12th Symposium, pp. 149- 154, 25-28 May 2005.
8. Zou Bengui; Cao Yanjie; Wu Jie; Wang Huijin; Chen Xuehui: Magnetic-Structural Coupling Analysis of Armature in Induction Coilgun, Plasma Science, IEEE Transactions, vol. 39, no 1, pp.65-70, Jan. 2011.

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PISTOLET Z WYRZUTEM ELEKTROMAGNETYCZNYM – PROJEKT I KONSTRUKCJA

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STRESZCZENIE *Opisano elektromagnetyczną wyrzutnię pocisków ferromagnetycznych. Wykazano, że konstrukcja z pojedynczą cewką, bez czujników, jest w stanie nadać pociskowi odpowiednią energię i dużą prędkość. W artykule opisano i przeanalizowano poszczególne kroki, takie jak dobór cewki i układu zasilania, obliczenia wstępne, urządzenia badawcze oraz badania produktu końcowego.*

Przedstawiono analizę MES modelu układu cewki wyrzucającej, kondensatora magazynującego energię i układu przełączania – zoptymalizowano poszczególne elementy układu ze względu na optymalne wymiary cewki.

Pistolet-wyrzutnię zaprojektowano i wykonano jako eksponat wystawowy, w którym prędkość nadawana pociskowi jest stosunkowo niewielka, znacznie mniejsza niż w przypadku przeznaczenia do strzelania.

Słowa kluczowe: *pistolet elektromagnetyczny, elektronika, MES, siła elektromagnetyczna*

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