Comparative Study of Linear Induction Motor Guns and Coil-Guns for Naval and Ground-Based Artillery

Shreyas Maitreya, Bhushan Raghuwanshi, and Priyanka Paliwal

U_s	Stator supply voltage
R_s	Stator resistance
L_s	Stator inductance
R_r	Rotor resistance referred to stator side (assumed equal to stator resistance)
L_r	Rotor inductance
Q	edge effect correction factor
I_s	Stator current
I_r	Rotor current
L_m	magnetizing inductance
Φ	flux
p	no. of poles
τ	pole pitch
v	speed of runner
a, d	length and diameter of solenoid
$x(t)$	position of runner inside the solenoid from one end
$i_s(t)$, $i_r(t)$	stator and runner current
μ_0	magnetic permeability of free space
l	length of the side of the runner that is perpendicular to the magnetic lines of force in the solenoid
B	magnetic field
n	number of turns per unit length of the solenoid

S. Maitreya (✉) · B. Raghuwanshi · P. Paliwal
Department of Electrical Engineering, Maulana Azad National Institute of Technology, Bhopal, India

Sanjeevikumar et al. (eds.), *Advances in Renewable Energy and Electric Vehicles*,
Lecture Notes in Electrical Engineering 767,
https://doi.org/10.1007/978-981-16-1642-6_6

Table 1 Conventional medium Caliber Cannon versus electromagnetic launcher

Projectile parameters	Mauser	Electromagnetic
V_{max} (m/s)	1405	2300
Max. Acceleration (1000*g)	84	149
Mass (kg)	0.235	0.090
Energy at Target (MJ)	0.232	0.238
Launcher Parameters	*Mauser*	*Electromagnetic*
Bore diameter (mm)	30	14.5 × 32.7
Barrel length (m)	3.41	3.35

1 Introduction

In the case of artillery, conventional weapons launch projectiles carrying explosive warheads at high velocities to destroy and eliminate enemy targets. Such systems are expensive, dangerous, pose the risk of premature detonation and have a limited range and energy available on the target [1]. To mitigate the above-mentioned problems, the use of electromagnetic launchers capable of launching projectiles at hyper-velocities is being studied as a viable alternative to conventional chemical propellant-driven artillery [2]. Table 1 presents technical superiority of electromagnetic launchers over conventional chemical propellant-driven launchers used in ground combat. The comparison is carried out between a Mauser 30 mm MK-32 Cannon and a traditional electromagnetic launcher.

The higher projectile velocity, higher acceleration and higher energy to mass ratio of the electromagnetic launcher in comparison to the Mauser cannon [23] make it a superior alternative to conventional artillery. Electromagnetic launchers especially railguns and coil-guns have been a subject of research since the 1970s, but current research on electromagnetic launcher mainly focussed on the electromechanical parameters of the coil-guns [4, 5]. Along with presenting both computer simulations and hardware implementation of the coil-gun, this paper also speaks on their on-field deployability[5] In the case of electromagnetic launchers, three types of hyper-velocity electromagnetic launchers are being extensively studied viz. railguns, linear induction motor guns and coil-guns [6].

2 Basic Design of Coil Gun

Railguns are beyond the scope of this study, and the main area of focus shall be exclusively on linear induction motor guns and coil-guns. The main operating principle of both these weapons is indicated, i.e. Lenz's law and the key differences between these weapons are mainly in their mechanical performance which is discussed in the subsequent sections. As shown in Fig. 1, coil-gun is an electromagnetic launcher that consists of a solenoid(s) that acts as the stator and a runner. The principle of operation

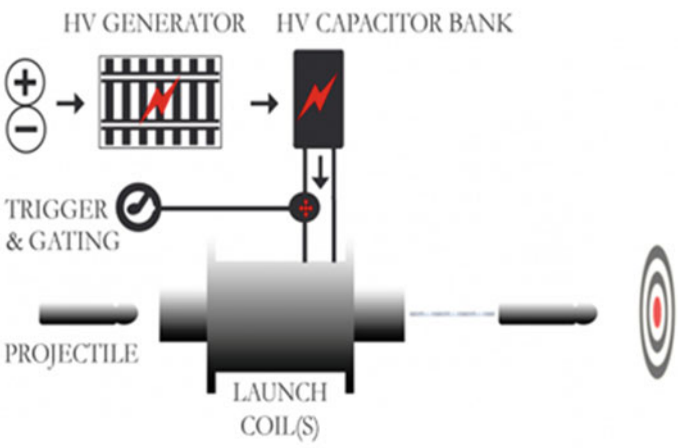

Fig. 1 Schematic of coil gun [2]

of a coil-gun is identical to that of a conventional linear induction motor except for the fact that a linear induction motor works on AC whereas coil-gun works on DC.

The use of DC in place of AC reduces the effects of the oscillatory nature of the force that is produced because of the alternating nature of the current that is supplied to the stator in the case of a linear induction motor gun. This aspect will be covered in greater detail in the subsequent sections.

3 Modelling of Linear Induction Motor Gun

This section presents a discussion on the modelling of a linear induction motor gun. Figure 2 presents a schematic of a rotary induction motor [1]. The development of a rotary induction motor into a linear induction motor is presented in Fig. 3.

As shown in Fig. 3, a linear induction motor is essentially a conventional rotary induction motor (Fig. 2) that has been cut along an axial plane and then laid on a flat surface [6]. Such a motor consists of a stator which is the stationary part and a runner which is the travelling part.

The stator in a linear induction motor produces a travelling magnetic field instead of a rotating one which is in the case of a rotary induction machine. The runner chases the travelling magnetic field and tries to catch it as per Lenz's law [6]. The stator and the runner are often referred to as the primary and secondary, respectively, and these terms will be used interchangeably hereafter throughout the paper. The runner shall also be referred to as the projectile. A linear induction motor's performance can be studied by analysing its equivalent circuit both in the a–b–c frame and stationary frame [6]. The equivalent circuit of linear induction motor in the a–b–c frame is presented in Fig. 4.

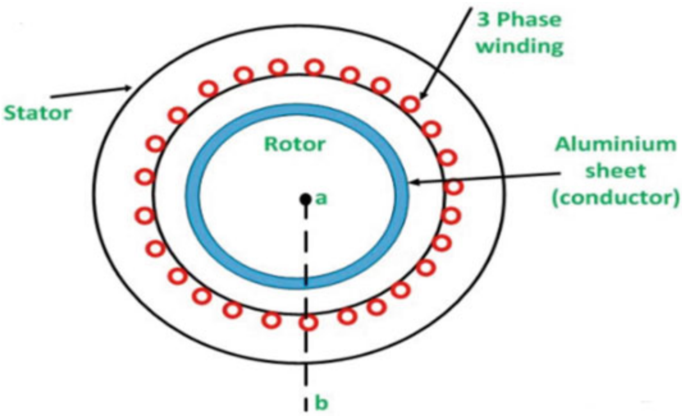

Fig. 2 Schematic of a rotary induction motor [1]

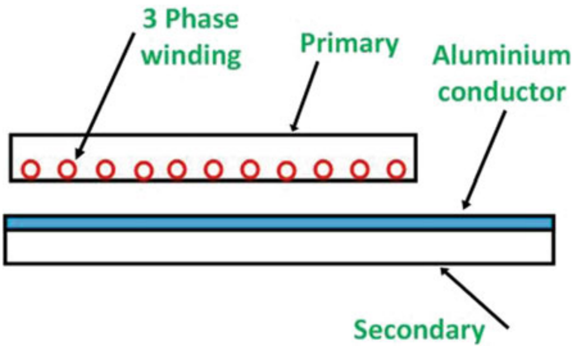

Fig. 3 Rotary induction motor developed into linear induction motor [1]

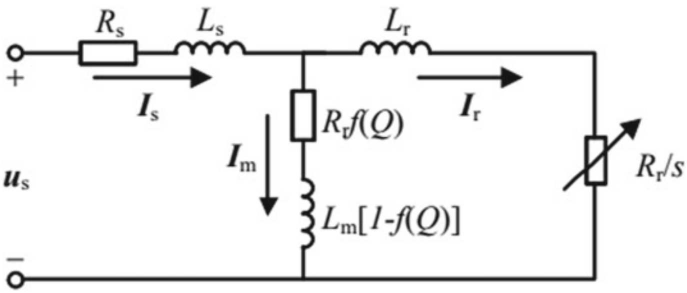

Fig. 4 Per phase equivalent circuit of linear induction motor in a–b–c reference frame

The edge effect comes into play in a linear induction motor because the distribution of flux in a linear induction motor is asymmetrical unlike that in a rotary induction motor because of a uniform air gap between the stator and rotor of a rotary induction motor which is absent in a linear induction motor. The end effect factor of the linear induction motor is determined from the expression as follows:

$$Q = \frac{\mathrm{DR_r}}{(L_\mathrm{m} + L_\mathrm{r})v} \tag{1}$$

The function that governs the effect of the edge effect factor on the various properties of the linear induction motor is given by:

$$f(Q) = \frac{1 - e^{-Q}}{Q} \tag{2}$$

Now, the correction values of rotor resistance and magnetising induction can be determined with the help of Eq. (2

$$R\prime_\mathrm{r} = R_\mathrm{r} f(Q) \tag{3}$$

$$L\prime_\mathrm{m} = L_\mathrm{m}(1 - f(Q)) \tag{4}$$

Now, writing the voltage equation of the linear induction motor in the stationary reference frame, the voltage matrix can be constructed as follow:

$$\begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} i_{s\alpha} & i_{r\alpha} & \Phi_{s\alpha} & 0 \\ i_{s\beta} & i_{r\beta} & \Phi_{s\beta} & 0 \\ i_{r\alpha} & i_{s\alpha} & \Phi_{r\alpha} & \Phi_{r\beta} \\ i_{r\beta} & i_{s\beta} & \Phi_{r\beta} & -\Phi_{r\alpha} \end{bmatrix} \begin{bmatrix} R_\mathrm{s} + R\prime_\mathrm{r} \\ R\prime_\mathrm{r} \\ \frac{\mathrm{d}}{\mathrm{d}t} \\ \omega_r \end{bmatrix} \tag{5}$$

From the above matrix, the equations for flux are determined as follows:

$$\Phi_{s\alpha} = L_s i_{s\alpha} + L'_\mathrm{m}(i_{s\alpha} + i_{r\alpha}) \tag{6}$$

$$\Phi_{s\beta} = L_s i_{s\beta} + L'_\mathrm{m}\left(i_{s\beta} + i_{r\beta}\right) \tag{7}$$

$$\Phi_{r\alpha} = L_r i_{r\alpha} + L\prime_\mathrm{m}(i_{s\alpha} + i_{r\alpha}) \tag{8}$$

$$\Phi_{r\beta} = L_r i_{r\beta} + L\prime_\mathrm{m}\left(i_{s\beta} + i_{r\beta}\right) \tag{9}$$

From Eq. (6), the electromagnetic thrust acting on the runner is given by,

Table 2 Parameters of linear induction motor gun

Parameter	Value
Inverter Bus Voltage	400 V
Mass of runner(kg)	2
Pole pairs	8
Pole pitch	0.15
T_s (sSeconds)	1e–5

$$F_e = \frac{3\pi p}{8\tau}\left(\Phi_{s\alpha} i_{s\beta} - \Phi_{s\beta} i_{s\alpha}\right) \tag{10}$$

The net mechanical force acting on the block is given by

$$F_{net} = m\frac{dv}{dt} = F_e - F_{losses} \tag{11}$$

$$m\frac{d^2 x}{dt^2} = \frac{3\pi p}{8\tau}\left(\Phi_{s\alpha} i_{s\beta} - \Phi_{s\beta} i_{s\alpha}\right) - F_{losses} \tag{12}$$

From the above equation, it can be inferred that the force on the runner is oscillatory since the currents in both α and β axes are sinusoidal.

Since, a dedicated block for a linear induction motor is not available on SIMULINK, the above equations were used, and a MATLAB code was written in the MATLAB workspace to study the behaviour of a linear induction motor. The parameters of linear induction motor gun are presented in Table 2.

Figure 5 presents the thrust-time graph of a linear induction motor. From Fig. 5, it is clear that the thrust, i.e. the force acting on the runner is highly oscillatory, thereby grossly limiting the destructive force of the gun by limiting the peak velocity due to the fluctuating nature of the direction of the acceleration vector of the projectile.

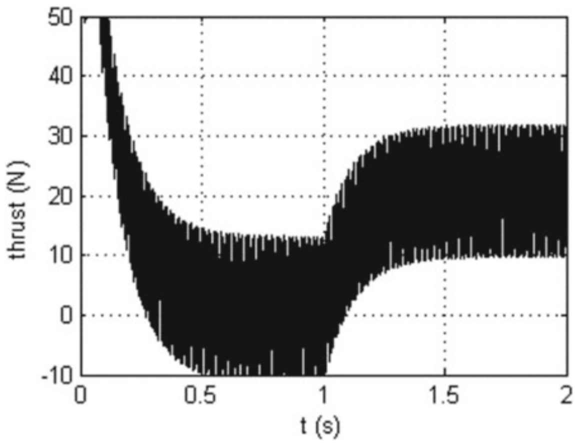

Fig. 5 Thrust-time graph of linear induction motor

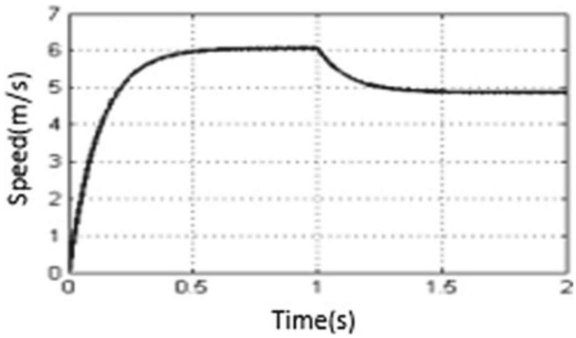

Fig. 6 Speed-time graph of the runner in a linear induction motor

Figure 6 presents the speed-time graph of the runner in a linear induction motor. Figure 6 shows another key limitation of a linear induction motor gun which is the low muzzle velocity of the projectile.

4 Performance Analysis of Coil Gun

Figure 7 presents the magnetic field inside a solenoid at any point on the axis of the solenoid. As shown in Fig. 7, each of the coils of a coil-gun can be regarded as a solenoid of finite length with the runner at point P, and its electromagnetic parameter can be determined from Eq. (13).

From Biot-Savart law, the expression for the magnetic field inside the solenoid comes to be:

$$B = \frac{\mu_0 i(t)_s}{2}\left(\frac{a}{\left(x(t)^2 + a^2\right)^{0.5}}\right) \tag{13}$$

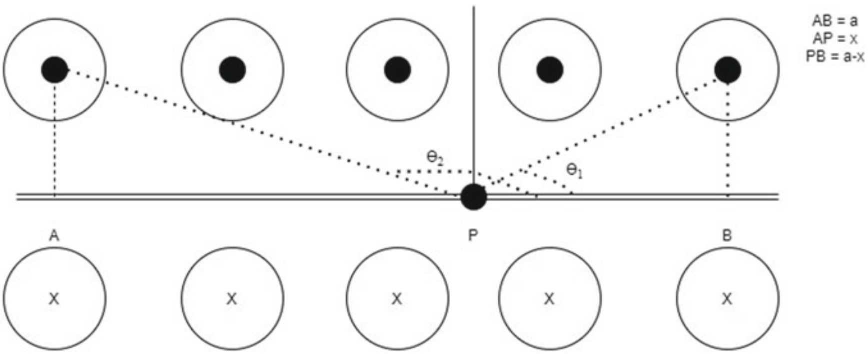

Fig. 7 Magnetic field inside a solenoid

Force acting on a current-carrying conductor in a magnetic field is given by

$$F = i\left(\vec{l} \times \vec{B}\right) \tag{14}$$

Force acting on the runner is given by,

$$F = i_{\mathrm{r}}(t)\left(\frac{l\mu_0 i_{\mathrm{s}}(t)}{2}\left(\frac{a}{\left(x(t)^2 + a^2\right)^{0.5}}\right)\right) \tag{15}$$

From Newton's second law,

$$m\frac{\mathrm{d}^2 x}{\mathrm{d}^2 t} = i_{\mathrm{r}}(t)\left(\frac{l\mu_0 i_{\mathrm{s}}(t)}{2}\left(\frac{a}{\left(x(t)^2 + a^2\right)^{0.5}}\right)\right) \tag{16}$$

Solving the above differential equation gives us an estimate of the position of the runner. It must be noted that the above equations have been derived by assuming that the size of the runner is negligible in comparison to that of the stator [11].

5 Simulation Results and Discussion

A coil-gun can be treated as a series R-L load. To meet the extremely high current demand of a coil-gun, it is generally powered by a capacitor bank of high voltage and high capacitance [7, 8] (Table 3).

A coil-gun is generally set up as shown in Fig. 8.

The capacitors need to be charged up to 400 V DC, and once the capacitors are charged, they are disconnected from the primary power supply [9, 10] and connected across the coils [2, 11]. Which are triggered as per the following sequence:

COIL 1 is turned ON initially when the projectile is initially at rest. The projectile is pulled into the coil. Once fully inside COIL-1, switching circuit 1 is turned OFF and the projectile continues to move through the coil on account of its inertia [12].

The sequential turn ON and turn OFF of each of the coils is necessary for the creation of the travelling magnetic field which will cause the projectile to advance through the barrel and acceleration [13].

Table 3 Simulation parameters

Parameter	Value
Number of stages	3
Power supply	400 V, 3900 *mF* capacitor bank
Total barrel length	100 mm

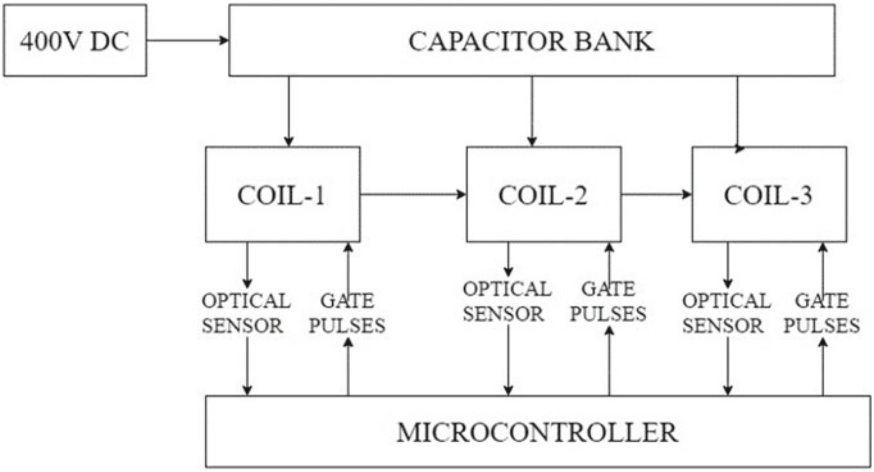

Fig. 8 Generic block diagram of 3 stage coil-gun

Figures 9 and 10 represent the force–time and speed-time graph, respectively, for coil gun. From Fig. 9, it can be observed that the force acting on the projectile although variable in magnitude maintained a positive direction up to 2.71428 ms after reversing its direction for a brief period before becoming zero. This allows the projectile to have a greater peak velocity, i.e. 35 m/s as seen in Fig. 10 for the same supply voltage of 400 V because of the positive direction of the thrust vector for most of its operating period. Most importantly, the projectile fired by a coil-gun reaches its peak velocity within 3 ms, whereas one fired by a linear induction motor gun takes almost 1 s apart from being several orders of magnitude slower. A lower firing time allows for quick reloading of the gun, in this case resulting in a theoretical firing capacity of more around 368.42 shots per second instead of a mere 1 shot per

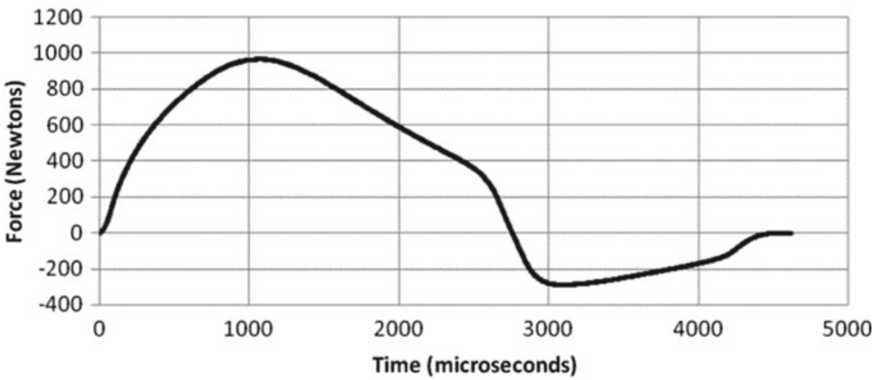

Fig. 9 Force–time graph for coil-gun

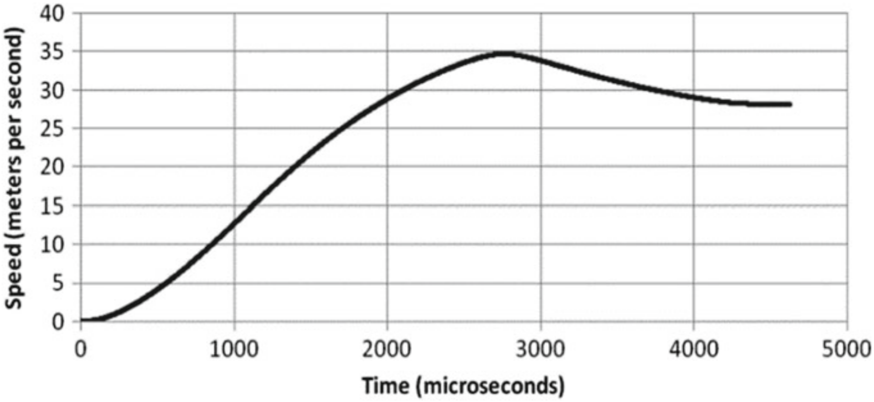

Fig. 10 Speed-time graph for coil-gun

second which could be achieved by the linear induction motor gun. This ensures that a greater number of targets can be engaged with further bolstering the destructive capabilities of the coil-gun w.r.t a linear induction motor gun.

6 Conclusion

The increased destructive power, reduced wear and tear and improved efficiency of a coil-gun combined with its reduced operating cost per shot make it a viable alternative to conventional chemical-driven weapons as seen in the introductory section(s) of the paper. Further, in comparison to other electromagnetic weapons, it can be concluded from the above simulations, it can be concluded that coil-guns are superior to linear induction motor gun as the projectile fired by the coil-gun is 35 times faster and can fire 368 shots per second such a high number of shots per second allows a coil-gun to have the range and capacity of an artillery gun but with the firing speed of an infantry weapon both in terms of muzzle velocity and the number of shots fired in each second. The Achilles' heel for coil-guns is not their range or destructive power but the availability of sufficient electrical power to sustain such a high number of shots per second for the entire course of a given battle if not a war. For coil-guns to become mainstream, advancements in power-supply technology are required so that they can be battle-ready under any circumstances.

References

1. A. Balikci, Z. Zabar, L. Birenbaum, D. Czarowski, On design of electromagnetic launchers for super velocity launchers. IEEE Trans. Magn. **43**(1), 107–110 (2007)

2. J.T. Tzeng, E.M. Schmidt, Comparison of electromagnetic and conventional launchers based on Mauser 30-mm MK 30–2 Barrels. IEEE Trans. Plasma Sci. **39**(1), 149–152 (2011)
3. N.S. Brahmbhatt, *Design and Optimization of an Electromagnetic Railgun*, Open Access Master's report, 2008, Houghton
4. Y.A. Dreizin, *Electromagnetic Launcher with Advanced Rail and Barrel Design*, United States of America, US5483863A, Patent 16 January 1996
5. S.J. Tatake, K.J. Daniel, K.R. Rao, A.A. Ghosh, I.I. Khan, Railgun. Defence Sci. J. **47(**3), 257–262
6. F. Korkmaz, I. Topaloglu, R. Gurbuz, Simulink model of vector controlled linear induction motor with end effect for electromagnetic launching system. Elektronika Ir Elektrotechnika **20**(1), 29–32 (2014)
7. Z. Zabar, Y. Naot, L. Birenbaum, E. Levi, P.N. Joshi, Design and power conditioning for the Coil-gun. IEEE Trans. Magnetics (1989). ieeexplore.ieee.org
8. J.L. He, Z. Zabar, E. Levi, B. Birenbaum, Transient performance of linear induction launchers fed by generators and capacitor banks. IEEE Trans. Magn. **27**(1), 585–590 (1991)
9. K. Chan, G. Clark, D. Helmlinger, D. Ng, S.A. McAfee, *Electromagnetic Coil-gun Final Report*, 2013, Reutgers School of Engineering, New Jersey
10. A. Balikci, High-velocity linear induction launchers. Int. J. Impact Eng., 1405–1409 (2008)
11. J.H. Gully, Power supply technology for electric guns. IEEE Trans. Magn. **27**(1), 329–334 (1991)
12. J.L. He, E. Levi, Z. Zabar, L. Birenbaum, Y. Naot, Analysis of induction-type coil-gun performance based on cylindrical current sheet model. IEEE Trans. Magn. **27**(1), 579–583 (1991)
13. H.M. Mohamed, M.A. Abdalla, A.A. Mitkees, W. Sabry, *Investigation on Electromagnetic Launching for Single Stage Coil*-gun, 2014, Military Technical College, Cairo