CHARACTERISTICS SIMULATIONS OF THE ELECTRODYNAMIC RAILGUN DIFFERENT CONSTRUCTIONS AND THEIR MEASUREMENT VERIFICATION

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Abstract

The transient characteristics for three different constructions of electrodynamic railguns were simulated and compared with the measurement curves. They concerned the ironless (IL), iron-core (IC) and those iron with permanent magnet (ICPM) railguns. The rail dimensions and configurations as well as the supply systems were the same. The simulations were carried out using the own field-circuit numerical model. The modelling results were compared with those obtained from measuring tests and good agreement was obtained.

1 Introduction

The linear motors market heavily depends on special civil or military applications. As the motors initial installation cost is higher, compared to the usually used electric drives, they have impacted the market less than expected. However, some research is leaded, to achieve better and better electromagnetic parameters for this devices [1].

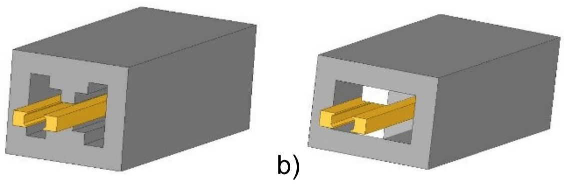
The research on the electrodynamic accelerators (EA), called railguns, are mainly devoted to military applications [2]. However, more and more investigations are related to their industrial applications like an impact testing for some materials [3]. Taking into account their supplying, in both applications, the main objective of the research is increase in their efficiency. Moreover, the active controlling and rising of the velocity of the projectile (bullet), which is located in a cartridge called sabot or armature, constitutes also the important topic of the research [4, 5].

One of the method of improving EA systems can be the increase of magnetic flux in the armature volume. This can be effected by amperage increasing of the current or by changing in the structure geometry. In the devices for percussive tests of materials, we can increase the energy and magnetic flux through changing of magnetic circuit geometry, as well. To do that, we can solute the magnetic field problem using partial differential equations (PDE) or preliminary calculate magnetic circuit of the railgun system, at least. The electromagnetic parameters from the railguns magnetic flux analyses are necessary for the field-circuit method which has been applied in this work.

For the electromagnetic actuators, which are to be applied to percussive testing of materials the armature transient characteristics are necessary. Including the mass and geometry of the armature, and parameters of the electrodynamic system, as well as the power supplying circuit, we worked out the field-circuit method for prediction of transient currents and energy values of the three railguns, as well.

2 Physical model

Three physical models of the railguns were designed and manufactured within this research. To facilitate laboratory tests, their rails (bus bars) were relatively short (30 cm). The calculation and measurement results were analysed and compared for them. The investigations concerned: ironless (IL), iron-core (IC), and iron-core with permanent magnets (ICPM) constructions (railguns). Two of them are schematically presented in Fig.1.



a) b)

Fig. 1 Outlines of the railgun prototypes a) IC; b) ICPM

3 Numerical model of the accelerators

In the pursuit of interactive design, we tried to reduce the computation time to a minimum. We tested that for the investigated accelerators (Fig. 1), with a relatively small cross-section of the rails (buss-bars), the phenomenon of eddy currents has no decisive impact on the armature dynamics. Therefore, we decided that instead of the difficult solving of time PDEs [5]

$$\nabla \times \left(\frac{1}{\mu}\nabla \times \boldsymbol{A}\right) = -\sigma\frac{\partial \boldsymbol{A}}{\partial t} - \sigma\nabla V + J, \qquad (1)$$

we used the field-circuit model of the actuators. Our calculations can be more effective after dividing them into two parts of execution. Part 1 concern the calculation to predict electromagnetic parameters of the three constructions by 3D numerical magnetic field analysis using the finite element method – FEM. In the part 2, the field-circuit method has been applied to transient analysis to predict the electrical and mechanical parameters. The part 1 has been carried out using model T-Ω in the Maxwell software [5]. Two types of boundary conditions have been used: the voltage boundary condition on the rails ends (Fig. 2b) and zero Dirichlet condition on the outer boundaries of the whole accelerator (Fig. 2a). The nonlinear B-H curve of the iron core has also been included in the modelling.

a) b)

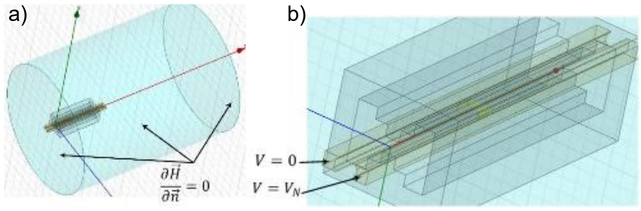


Fig. 2. IC accelerator: a) zero Dirichlet boundary conditions; b) voltage boundary conditions on rails ends

The equations for the field-circuit model describing the motion of the projectile and the current intensity waveform (under voltage excitation) were formulated using the Euler-Lagrange method:

$$\frac{dv}{dt} = \frac{F(i,z) - Dv - D_p v^2}{m} \quad (2)$$

$$\frac{di}{dt} = \frac{-Ri - \frac{d}{dz}(\Phi_s(i,z))v - \frac{q}{C}}{L_d(i,z)} \quad (3)$$

where: z - projectile (bullet) position, v - its velocity, m - projectile mass, D and D_p - kinetic and air friction coefficients, R – the circuit resistance, i - current intensity, C - capacitance, $F(i,z)$ – electrodynamic force, $\Phi_s(i,z)$ - magnetic flux, $L_d(i,z)$ - dynamic inductance.

4 Calculation results and measurement verification

The mathematical models were verified experimentally for different values of initial capacitor voltage. It should be emphasized that for the tested accelerator designs the repeated measurements of excitation current waveforms and voltage on capacitor banks were executed and good reproducibility was obtained. In Fig. 3 an exemplary measurement verifications of the field-circuit model for IL, IC and ICPM railguns are presented. A good conformity is observed.

The measurement verification of the calculated values of the projectile (bullet) velocity was carried out, as well (Table 1). Some differences are observed for ICPM construction. It is mostly due to neglecting of eddy currents in the field analysis of the magnetic circuit consisted of permanent magnets and the solid iron core.

The use of the ferromagnetic core (IC) caused approximately 3 times higher bullet velocities compared to the iron-less (IL) railgun. In the case of ICPM construction, the projectile velocity increased nearly 4 times in reference to the IL physical model. However, under the excitation current value 43 kA, and the voltage of 148 V, the higher bullet velocity is observed for IC construction in comparison with the ICPM physical model.

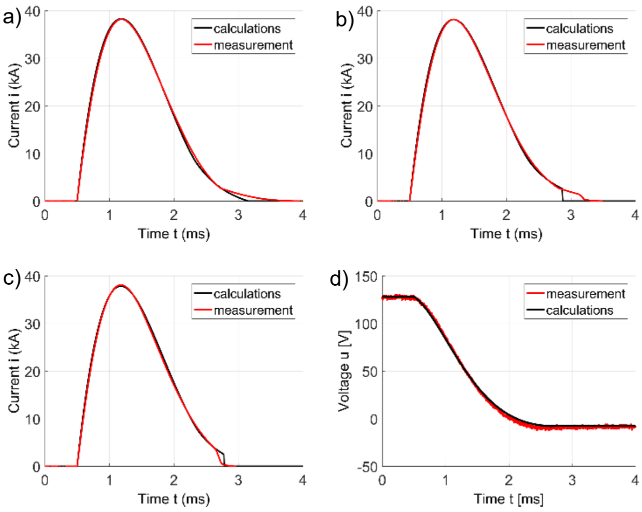


Fig. 3. Measurement verification of the field-circuit models under voltage of U=128 V: a) IL construction; b) IC model, c) ICPM construction, d) voltage wave

***U* [V]**	**IL**		**IC**		**ICPM**	
	v_{meas}	v_{calc}	v_{meas}	v_{calc}	v_{meas}	v_{calc}
70	12.8	13.0	39.8	40.4	52.1	52.9
100	32.3	34.8	85.0	82.7	85.6	94.7
128	60.1	62.7	141.2	135.6	123.3	145.1
148	77.2	82.9	179.9	170.9	151.7	176.1

Table 1. Measurement verification of the projectile velocity $\boldsymbol{v}$ in [m/s]

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