Hybrid pneumatic-electromagnetic launcher - general concept, mathematical model and results of simulation

Abstract. The electromagnetic launcher is a specific type of electromechanical converter. Electrical energy from the power supply, discharging in the pulse way, is used for acceleration a moveable element (bullet). The electromagnetic launchers are widely used in applications ranging from military applications and ending on the basic research on the physical properties of materials. This paper presents the results of research conducted in the Department of Mechatronics, which included an analysis of the mathematical model (field-circuit) of the hybrid electromagnetic launcher with pneumatic assist. The purpose of this article is to present the results of simulations.

Streszczenie. Wyrzutnia elektromagnetyczna to specyficzny rodzaj przetwornika elektromechanicznego. Energia elektryczna pozyskiwana ze źródła prądu stałego, rozładowywana w sposób impulsowy, jest wykorzystywana do procesu rozpoczęcia elementu ruchomego (pociągu). Wyrzutnie elektromagnetyczne mają szerokie zastosowania począwszy od zastosowań militarnych a kończąc na badaniach fizycznych własności materiałów. W artykule przedstawiono wyniki badań symulacyjnych, przeprowadzonych w Katedrze Mechatroniki Politechniki Śląskiej, dla hybrydowej wyrzutni elektromagnetycznej ze wspomaganie pneumatycznym. (Hybrydowa wyrzutnia pneumatyczno-elektromagnetyczna - ogólna koncepcja, model matematyczny oraz wyniki badań symulacyjnych).

Keywords: electromagnetic launcher, coilgun, railgun.
Słowa kluczowe: wyrzutnia elektromagnetyczna, wyrzutnia elektromagnetyczna o napędzie cewkowym oraz szynowym.

Introduction
The idea of electromagnetic acceleration is a concept that was introduced at the beginning of the twentieth century. The first device implementing the construction electromagnetic acceleration was in 1920. This construction was named “the electric cannon” [2]. Actually there are also in use the following terms: electromagnetic launcher or electromagnetic gun. The rise in the intensity of research on electromagnetic accelerators was observed during the period of the Second World War when many laboratories experiments were carried out in various German research centers oriented at military applications. At that time main difficulty in developing this type of electromagnetic devices was lack of appropriate sources of energy. Intensive development of pulse power supplies, capacitors and supercapacitors in the end of 20th century caused again significant interest in electromagnetic launcher theme. Nowadays many research centers all over the world work on problems related to design, construction, optimization and new applications of electromagnetic launchers.

Let us remind that the electromagnetic launcher is a specific type of an electromechanical converter in which the electrical energy obtained from a DC source is used for rapid acceleration of a movable element (projectile). It is worth underlining that maximum velocity of the moveable element which can be obtained in electromagnetic launcher is very high (even tens of times greater than the speed of sound) what results from very sudden process of releasing large amounts of electrical energy which in very short time is converted in mechanical kinematic energy [2,9].

The electromagnetic launchers can be divided into two basic categories:
- coilgun in which the movable element made of a ferromagnetic material is placed inside a coil producing magnetic field [1],
- railgun in which a movable copper element is placed between two rails carrying current [7].

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There are wide variety of possible applications of electromagnetic launchers as non-conventional linear drives. Among them there are some very sophisticated proposals: electromagnetic guns for war ships (military purpose), launchers for satellites (cosmic space technology), high-pressure (for advanced physical research) or simulator of collisions between meteoroids and the surface of the Earth [1,3,4,5,6].

As regards pneumatic launcher, its concept is older than the concept of electromagnetic gun. Even a very popular air gun can be treated as simple example of a pneumatic launcher.

Main idea of this paper is to integrate and put together in one common construction: an electromagnetic launcher and a pneumatic launcher. This construction will be further termed a pneumatic-electromagnetic launcher. The authors present advantages of such a solution resulting from results of simulations. It is worth emphasizing that the prototype of a pneumatic-electromagnetic launcher was constructed and the elaborated mathematical model was experimentally verified [8].
The general concept of the hybrid launcher as a multidimensional control object

The hybrid pneumatic-electromagnetic launcher whose general concept is presented in Fig.3. consists of:
- pneumatic module (denoted further as a module P) whose task is to start motion of a moveable element and to give its introductory velocity,
- electromagnetic module equipped in a coil (denoted further as a module C) whose task is to continue acceleration process,
- electromagnetic module equipped in a rails (denoted further as a module R) whose task is to finalize acceleration process.

As can be seen in Fig. 4, there are 5 input (control) variables which can be adjusted (before firing) by the launcher’s operator:
- $P_0$ – initial value of the argon pressure in the pneumatic module,
- $U_{C0}$ – voltage initial value for capacitors battery supplying module C,
- $U_{R0}$ – voltage initial value for capacitors battery supplying module R,
- $t_{on}(x_C)$ – moment of activating the module C,
- $t_{off}(x_C)$ – moment of deactivating the module C.

As the elaborated mathematical (circuit-field) model which will be presented in chapter 4 takes into account the following electrical and mechanical variables important for analysing launcher behaviour from viewpoint of monitoring problems, as well as control problems:
- $j^R(t)$ – instantaneous value of the discharge current for module R,
- $v^R(t)$ – instantaneous value of velocity of the movable element for module R,
- $x^R(t)$ – instantaneous value of displacement of the moveable element for module R,
- $a^R(t)$ – instantaneous value of acceleration of the moveable element for module R,
electromagnetic force determined with the help of finite element method. The two-dimensional function $F^C(x^C, i^C)$ is presented in Fig.6.

The electrodynamic force $F^R = f(x^R, i^R)$ acting upon the movement element in the module R, was calculated in similar way (with use of finite element method) and is presented in Fig.7.

The program of simulation allowing to investigate influence of input (control) variables on process of acceleration of the movement element was elaborated. The selected results of simulation oriented at time function of currents, displacements, velocities and accelerations for the module C and module R are shown in Fig.8.+Fig.11 and Fig.12.+Fig.15, respectively.

In the module R the greatest impact upon acceleration of the movable element has the first “half-wave” of the current flowing in the rails. In the time of the first “half-wave” the movable element achieves about 85% of the final (output) velocity.
In the module C the greatest impact upon acceleration has initial velocity $v_0^C$, initial battery voltage $U_{BC}$ and moments of the activating and deactivating module C. As may be seen, the optimum moment of activation should be determined in relation to the position of the moveable element along the coil.

In the case in point the best moment of activation ($t_{on}$) corresponds to the position of the moveable element equal to zero ($x_0^C = 0$).
Fig.16. The time plots of the velocity of moveable element $v^C$ in the module C for different moments of its activation, referred to the positions of the movable element along the coil $x^C_0$

Summary

Comparing the proposed hybrid 3-module pneumatic-electromagnetic launcher with the classical purely-electromagnetic single module, one can notice that the hybrid construction gives remarkably wider opportunity to influence acceleration process of the moveable element. It results from the fact that the number of input (control) values is increased to 5. It is also possible to interact with moveable element during its motion.

The elaborated mathematical (circuit-field) model and the results of simulation enable to determine the best strategy for acceleration and launching the moveable element.

REFERENCES


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