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Research on self-consistent control strategy of multistage synchronous induction coil launcher

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A B S T R A C T

Trigger control strategy is of vital importance for the multistage synchronous induction coilgun (MSSICG). According to the operating principle of MSSICG, we can theoretically obtain a sustained and steady acceleration which is sufficient to push the projectile to high speed by means of continuously increasing the series of driving coils and matching with the appropriate trigger strategy. However, the transition time between the adjacent coils decreases with the increase of the projectile velocity, which leads to the weakness of the traditional position or time trigger control. In this paper, a self-consistent control strategy of MSSICG was proposed. Its accuracy and flexibility are verified through an illustrative example of a 25 stages synchronous coilgun. The results coincide well with that by finite-element method (FEM), and the error of muzzle velocity is only 3.4%. Based on this method, the influence of slip speed and rise length on the adaptive control effect is calculated and analyzed, and accordingly proposed to use variable slip speed. As far as the capacitive pulsed power supply (CPPS)-based MSSICG is concerned, the research methods and results in this paper have both theoretical and pragmatic value in simplifying the design process and improving energy conversion efficiency (ECE).

1. Introduction

Electromagnetic launcher (EML) is a revolutionary weapon that uses the electromagnetic (EM) force to do the work to convert the electric energy stored in the power system into the kinetic energy of the payload, so as to achieve the high speed or super high speed launching [1,2]. EML technology has great potential advantages and broad application prospects in both military and civilian fields. The main application prospects in the civil fields include passenger transport [3], EM levitation [4], EM braking and inertial confinement fusion research, etc. However, it is indisputable that military applications are the most practical and promising fields of EML technology. The applications on the tactical level mainly include the EM mortar [5], missile launch assist [6], EM aircraft launch system (EMALS) [7], etc., that of the strategic level is represented by the space-based antiballistic missile and nantisatellite systems.

MSSICG has become one of the most important branches of the EML with the unique advantages such as greater thrust, higher efficiency and reusability (due to no contact, arc and erosion), simpler switching device (small pulsed current required). Therefore, many researchers have conducted extensive theoretical and experimental researches on the MSSICG. A 40 stages coilgun was successfully operated to accelerate 340-g aluminum armature to 406 m/s [8]. In 2004, Sandia National Laboratories and Lockheed Martin MS2 successfully employed a 5 stages induction coilgun for a missile launcher of 650-kg sled with peak vertical height of 7.3 m and peak velocity of 12 m/s [6]. A 5-kg copper armature was accelerated to 220 m/s through a 15 stages coilgun [9]. A 160-stage coilgun with 31 MJ energy stored can accelerate a 5 kg projectiles to 2040 m/s [10].

Driving coils must be sequentially triggered to ensure that the magnetic traveling wave and the motion of the projectile are kept approximately synchronous. Although the basic principle of MSSICG is simple, it is difficult to build a more convenient and universal trigger scheme for high velocity and high ECE launch because of its complicated electromechanical coupling process. Therefore, trigger strategy has become an important bottleneck restricting the development of high-middle velocity MSSICG [11]. The present control strategies are mainly divided into two categories: one is mainly based on 'try-see' method or numerical approach or intelligent algorithms, represented by simple timing control [12], position trigger control [13] and soft trigger control

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Nomenclature

MSSICG	multi-stage synchronous induction coilgun
FEM	finite-element method
CPPS	capacitive pulsed power supply
ECE	energy conversion efficiency
EML	electromagnetic launcher
EM	electromagnetic
EMALS	electromagnetic aircraft launch system
ESI	equivalent single-turn inductance
MCEC	movement conductor eddy current
CFM	current filament method
V_c	voltage column vector
I	current column vector
R	diagonal matrix composed of current filament and coil resistance
L	diagonal matrix consisting of self-inductance
M	mutual inductance matrix
C	capacitance value of each stage
M_p	quality of the armature
x	displacement of the armature
l	center distance of two adjacent driving coils
λ_k	rise length corresponding to the *k*-th driving coil
N_k	number of turns of *k*-th driving coil
L	value of the equivalent single-turn inductance
β	coefficient that reflects the influence of armature on the equivalent inductance of coil
v_{silp}	slip speed between magnetic traveling wave and armature
h_i	axial length of *i*-th driving coil
w_i	radial thickness of *i*-th driving coil
$s_{i(i+1)}$	axial spacing of *i*-th and $(i+1)$-th driving coil
$s_{i(i\text{-}1)}$	axial spacing of *i*-th and (*i*-1)-th driving coil
w_a	wall thickness of the armature
h_a	axial length of the armature
r_a	inner radius of the armature
g_c	spacing between the coil and the barrel
t_b	wall thickness of the gun tube
Z_{ck}	position of *k*-th coil center
v_p	velocity of the armature

[14], while they are more applicable on launching large-mass, low-velocity armature. The other is the self-consistent scheme represented by WARP-10 [15] and its successor SLINGSHOT [16]. However, some of these crude assumptions are questionable, and there is no basis for selecting adjustable parameters.

Hence, in this paper, we present the research of a self-consistent control strategy. The influence of coil turns on the equivalent single-turn inductance (ESI) is considered to improve the calculation accuracy. Systematic differential equations and governing equations are established and a 25 stages EML with different circuit parameters for each stage is self-consistent designed. In order to verify the usefulness of the control strategy, the 25 stages coilgun are simulated using the time step transient finite-element method (FEM) rather than the expensive experiment. Then the quantitative analysis of the influence of the adjustable parameters including slip speed and rise length on the launch performance is conducted to provide guidance for their selection to improve ECE, and thereby reduce weight and volume of the CPPS.

2. Basic principle of MSSICG

MSSICG consists of the discrete solenoidal driving coils, the projectile made of cylindrical armature wrapping around the payload, CPPS and trigger control circuits etc. The basic schematic diagram of MSSICG is shown in Fig. 1. All equal-spaced driving coils are stacked end-to-end to form a flyway in which the projectile moves. The working process is as follows: the trigger controller sends signals to each switch sequentially to turn on the discharge circuits, and a magnetic traveling wave which moves just slightly faster than the velocity of the projectile can be created. According to Faraday's law, the time-varying magnetic field will introduce a current in the armature, which will attempt to exclude the magnetic flux from the armature. According to Lenz's law, the interaction between the induced eddy current and the magnetic traveling wave generates axial Lorentz forces that accelerate the armature axially [17].

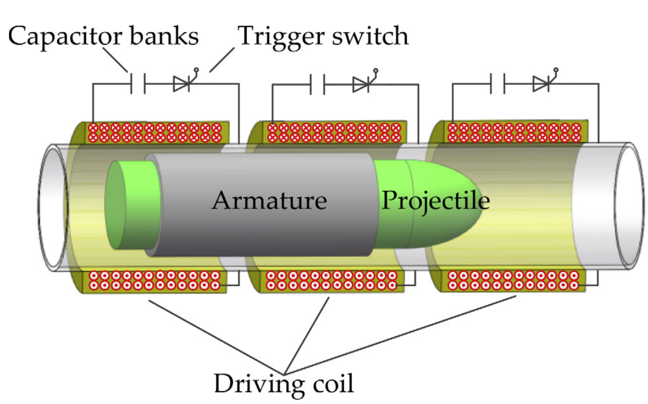

Fig. 1. Schematic of the multi-stage induction coil launcher.

3. Mathematical model

The dynamic simulation of MSSICG is a complex movement conductor eddy current (MCEC) field problem. From the viewing point of numerical calculation, it's very challenging because of the difficult problems in computational electromagnetics such as the calculation of EM, thermal, mechanical, structural coupling field and MCEC field; From the viewing point of engineering application, several vital parameters of armature such as the dynamic force, velocity and displacement can be obtained through the accurate numerical simulation technology, which has direct guidance on the experiment rehearsal and structure optimization, so as to improve the muzzle velocity and launch efficiency. The common numerical analysis method can be divided into two types: one is to use the circuit model-based numerical simulation software such as MATLAB, the other is finite element calculation based on the field-circuit coupling model. The field-circuit model can accurately solve the launching process. However, its time-consuming drawback makes it inexpedient to be used for the design or parametric optimization of MSSICG at high-middle speed. Compared with the field-circuit coupling model, the circuit model is widely used in a coil launcher's performance analysis because of its simple principle and easy realization.