



HIGH TEMPERATURE BALLISTIC IMPACT TEST TECHNOLOGY BASED ON ELECTROMAGNETIC LAUNCH

Chunyang Zhang¹, Jun Liu¹

¹School of Aeronautics, Northwestern Polytechnical University, Xi'an, 710072, China

Abstract

Considering the high temperature when aero-engine is working, it is necessary to carry out the ballistic impact test of the high temperature projectile penetrating target to study the blade containment at high temperature. This paper puts forward a ballistic impact test based on electromagnetic launch. A theoretical model, numerical model and a scaled test are established to verify the rationality of the method.

Keywords: Rotor blade containment, Ballistic impact test, Electromagnetic launch, High temperature

1. General Introduction

Despite the concerted efforts of engine manufacturers to mitigate the risk of uncontained rotor failures, incidents involving uncontained compressor and turbine rotors have persisted in recent years. A notable example occurred on October 28, 2016, when American Airlines Flight 383 experienced an uncontained rotor event at Chicago O'Hare Airport during takeoff. The right CF6-80C2B6 engine of the Boeing 767-300ER suffered a fatigue fracture of the high-pressure turbine (HPT) second-stage disk. The resulting high-velocity debris breached the engine casing, penetrated the wing and fuel tank, leading to fuel leakage and a subsequent fire. Investigations revealed that the turbine disk, constructed from nickel-based alloy 718, contained discrete dirty white spots (DDWS) — regions of white oxides or impurities introduced during the manufacturing process. Under the cyclic conditions of flight, these impurities facilitated the propagation of cracks in the DDWS regions due to the synergistic effects of temperature and stress, ultimately culminating in the disk's failure.



Figure 1 – The accident of American Airlines Flight 383

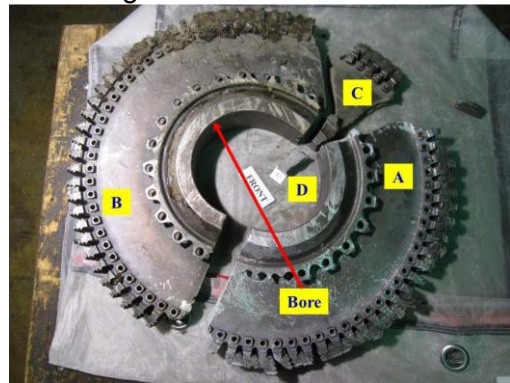


Figure 2 – Fragment of turbine disk

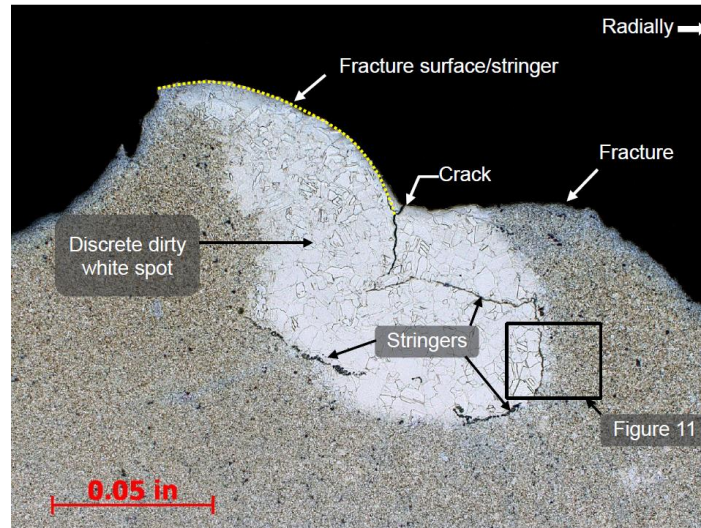


Figure 3 – SEM inspection of turbine disk fracture

Due to the challenges of environmental factors (such as bird strikes, environmental corrosion, and foreign object damage), manufacturing processes, and material defects, uncontained engine rotor events remain an occasional occurrence. Consequently, aviation authorities including the Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA), have each issued airworthiness standards for transport aircraft: FAR-25 and CS-25 respectively. These standards impose requirements on engine rotor containment to minimize the hazards associated with uncontained rotor failures.

The design of containment predominantly relies on numerical simulations combined with component testing. The engine casing containment test is crucial for validating the ability of the casing to retain rotor blades following a fracture event.

During the operation of a turbofan engine, the turbine section can reach temperatures as high as 1770°C, while the temperature inside the compressor casing can reach 400°C. When rotor components fracture and collide with the casing, the structure is subjected to both thermal and impact loads. Excessive impact stress may compromise the casing's integrity, failing to contain the fractured rotor, which can lead to secondary damage to the aircraft. Consequently, research into the containment capabilities of engine casings under thermal influences holds significant theoretical and practical value.

Rotor blade containment is an important research to ensure the safety and reliability of turbine engines. The internal environment and load of turbine engine are very complicated, which makes the blades inevitably suffer from material failure and fracture under the multiple influences, and high-speed debris from the turbine assembly ruptures the engine casing [1]. In order to analyze the impact resistance of the casing to debris, one of the most direct method is ballistic impact tests.

Air gun is a common high-speed loading equipment in ballistic impact test. But the air gun is slow in response, long in preparation period for launching, poor in air release accuracy, and greatly influenced by environmental factors such as temperature and humidity, so it is difficult to accurately control the launch speed of projectiles. In addition, some research [2, 3] attempts to carry out high-temperature ballistic impact test. when launching a high-temperature projectile with air gun, if the projectile is directly heated, the barrel will be heated at the same time, which will have a great impact on the service life of barrel. However, if the high-temperature projectile is put into the barrel through the heat insulation device before launch, it is limited by the long preparation period of air gun launching, resulting in a long cold contact time and large heat loss of the projectile. Due to the difficulty of launching high-temperature projectiles, the high-temperature ballistic impact test is only limited to the consideration of target temperature, and the problem of large temperature difference between the room-temperature projectiles and the high-temperature target remains to be solved.

The above problems of air gun can be effectively solved by using electromagnetic launch.

Electromagnetic launch technology is an innovative and advanced method that transforms electromagnetic energy into the kinetic energy required for launching. This technology can accelerate

loads ranging from a few grams to tens of tons to high speeds over relatively short distances, achieving launch velocities tens to hundreds of times greater than those attainable by air guns. Theoretically, the kinetic energy imparted to the projectile is limited only by the capacity of the electromagnetic energy source. With sufficient energy storage, the projectile can be accelerated to high or even ultra-high velocities. This capability is particularly valuable for testing the performance of structures under complex service conditions. Additionally, by adjusting the energy storage, different electromagnetic forces and projectile velocities can be achieved, offering superior control over the launch speed.

Electromagnetic loading provides substantial launch velocities within a very short duration, typically between 10^{-4} and 10^{-3} seconds. Compared to air gun systems, the barrel length of an electromagnetic launcher can be reduced to just 1-3 meters. And the electromagnetic loading does not produce airflow that could affect test results, ensuring better repeatability of experiments. Additionally, the electromagnetic force and the velocity imparted to the projectile during launch can be quickly calculated based on electromagnetic theory, facilitating the accurate assessment of test results.

There are two well-established technologies for electromagnetic launch, railgun and coilgun [4], which differ in launch method (Fig. 4).

The driving mechanism of a coilgun consists of one or more fixed coaxial coils of the same diameter. When the energy storage system accumulates sufficient electrical energy, it discharges through a trigger switch into the driving coil, creating a pulse current. This pulse current generates a pulsed magnetic field around the coil. As the magnetic field changes, it induces eddy currents in the projectile located near the driving coil. The interaction between these eddy currents and the magnetic field generates axial electromagnetic forces, propelling the projectile along its path. The coilgun has the characteristic that the launch preparation period is short, and the armature and barrel are not in contact with each other during launch, so the energy loss is less, the excessive loading current is not needed, and the service life of the barrel and armature is long, which is suitable for the test.

According to the requirements of ballistic impact test, an idea of testing based on electromagnetic coilgun launch technology is proposed to realize the test of high-temperature projectile impacting high-temperature target. In order to improve the launch speed of the projectile, multi-stage coil acceleration method is adopted to reduce the capacitance of each stage capacitor, so as to reduce the test cost and improve the safety of the test operation. In this paper, the theoretical model of multi-stage electromagnetic coilgun is established, and a scaled coilgun is established to verify the rationality of technical scheme. Further, the design of high temperature ballistic impact test will be prospected to study the blade containment.

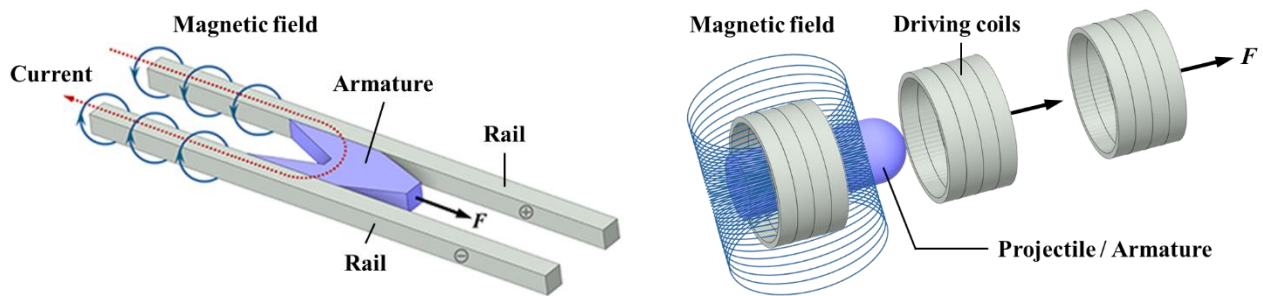


Figure 4 – Two electromagnetic launch technologies: railgun (left) and coilgun (right).

2. Theoretical Model of Electromagnetic Induction Coilgun

2.1 Equation of multi-stage coilgun

The multi-stage induction coilgun launch system consists of multi-stage coaxial fixed driving coils with the same diameter, each of which can be equivalent to an R-L-C circuit. Under the condition of uniform distribution of armature induction current, the armature circuit can be equivalent to an R-L circuit, and then the circuit of the multi-stage coilgun shown in Fig. 5 can be obtained.

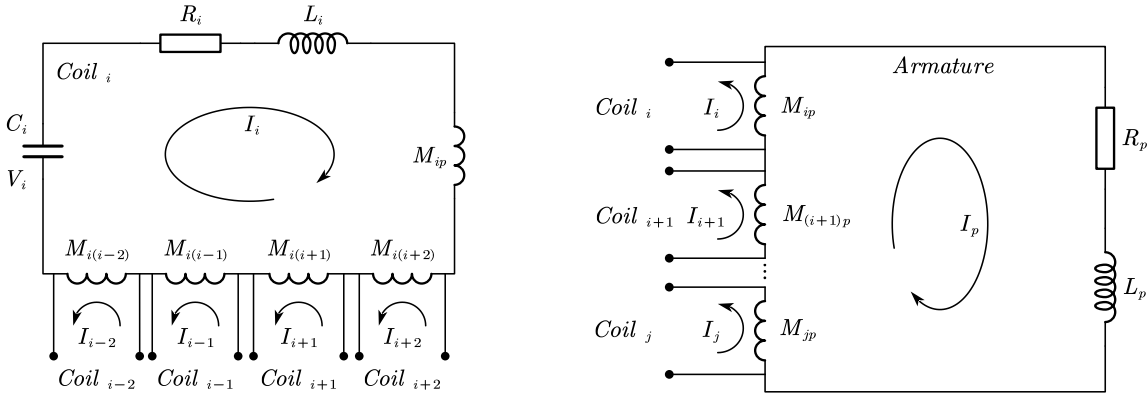


Figure 5 – Equivalent circuits of driving coil (left) and armature (right).

An N-stage coilgun consists of n coaxial driving coils and an armature (induction coils). The capacitance, initial voltage, self-inductance and resistance of each driving coil are C_i , U_i , L_i and R_i ($i = 1, 2, \dots, N$). The mutual inductance between the driving coils is M_{ij} ($i, j = 1, 2, \dots, N, i \neq j$) respectively, and $M_{ij} = M_{ji}$, and the mutual inductance between two or more coils is ignored. The self-inductance and resistance of armature are L_p and R_p respectively, and the mutual inductance between armature and driving coils is M_{ip} ($i = 1, 2, \dots, N$). The armature moving speed and distance at time t are v and x , respectively. According to Kirchhoff's voltage law and equations of motion, the ordinary differential equations (ODEs) of multi-stage coilgun launch can be established, in which the mutual inductance M_{ip} and the mutual inductance gradient dM_{ip} are functions of x related to the position of the driving coils and the armature, and can be solved by the equivalent current loop method.

$$\begin{aligned}
 L_p \frac{dI_p}{dt} + M_{1p} \frac{dI_1}{dt} + M_{2p} \frac{dI_2}{dt} + M_{3p} \frac{dI_3}{dt} + M_{4p} \frac{dI_4}{dt} + M_{5p} \frac{dI_5}{dt} \\
 = -R_p I_p - \left(\frac{dM_{1p} I_1}{dt} + \frac{dM_{2p} I_2}{dt} + \frac{dM_{3p} I_3}{dt} + \frac{dM_{4p} I_4}{dt} + \frac{dM_{5p} I_5}{dt} \right) \quad (\text{armature}) \\
 M_{1p} \frac{dI_p}{dt} + L_1 \frac{dI_1}{dt} \\
 = U_1 - R_1 I_1 - \frac{dM_{1p} I_p}{dt} - (M_{12} I_2 + M_{13} I_3) \quad (\text{coil 1})
 \end{aligned}$$

The acceleration process of the projectile is driven by the armature, and the total mass of the projectile and armature is m_p , so the motion equation can be established:

$$F_x = m_p \frac{dv}{dt}$$

Where F_x is the axial electromagnetic force on armature and projectile, which is usually calculated by virtual displacement method. When only one set of driving coils drives the armature, the total magnetic energy of the system composed of the driving coil loop and the armature loop at this time:

$$W = \frac{1}{2} L_1 I_1^2 + \frac{1}{2} L_p I_p^2 + M_{1p} I_1 I_p$$

Assuming that the armature moves dx along the axial direction under the action of electromagnetic force f_x , the electromagnetic force will do work $f_x dx$, and the magnetic energy in the system will change accordingly. Let the variation of magnetic energy be dW , since the self-inductance L_1 , L_p and the current I_1 , I_p remain unchanged, then:

$$dW = dM_{1p} I_1 I_p$$

According to the conservation of energy:

$$f_x = \frac{dM_{1p}}{dx} I_1 I_p$$

From this, it can be concluded that the motion equation of the projectile is expressed as follows under the joint promotion of five-stage driving coils:

$$m_p \frac{dv}{dt} = F_x = \sum_{i=1}^5 I_i I_p \frac{dM_{ip}}{dx}$$

$$\frac{dx}{dt} = v$$

The theoretical modeling of electromagnetic coilgun projectile launch process is realized based on eq. 1.

$$\left\{ \begin{array}{l} \frac{d[I]_{N+1}}{dt} = ([L]_{N+1} + [M_p]_{N+1})^{-1} ([U]_{N+1} - [R]_{N+1}[I]_{N+1} - v[dM_p]_{N+1}[I]_{N+1} - [M]_{N+1}[I]_{N+1}) \\ \frac{d[U_d]_N}{dt} = -\frac{[U_d]_N}{[C]_N} \\ \frac{dv}{dt} = \frac{1}{m_p} \sum_{i=1}^N I_i I_p \frac{dM_{ip}}{dx} \\ \frac{dx}{dt} = v \end{array} \right. \quad (1)$$

2.2 The solution of theoretical model

The theoretical model of N-stage coilgun consists of $2N+3$ multivariate ODEs, which can be solved by numerical method. The initial conditions should be given in the process of solving the ordinary differential equations. The $2N+3$ initial conditions of these ODEs are respectively: when the N^{th} driving coil is triggered at t_N , the initial current I_{IN} of the coils and armature, the driving voltage U_{IN} of the coils, the initial speed v and the initial position x of the armature and missile assembly. Since each stage of the coils is triggered at different times, all initial conditions should not be considered at the beginning of the calculation, but should be considered step by step with the trigger of this stage of the coil when $t = t_N$, and the determination of t_N depends on the position of the projectile. When the projectile runs between the two stages of the coils, it is considered that the current time t_N is the trigger time of the next coil.

General numerical calculation methods of ODEs include forward difference method, improved Euler method, Runge-Kutta method and Adams method. Considering the complexity of ODEs, in order to improve the accuracy and efficiency, these methods are used to solve respectively (Fig. 6), and finally the coil current and armature current curves, the velocity curve, displacement curve of the armature and missile assembly can be obtained (Fig. 7). This theoretical model can be used to explore the launch parameters of electromagnetic coilgun and the motion response of projectile.

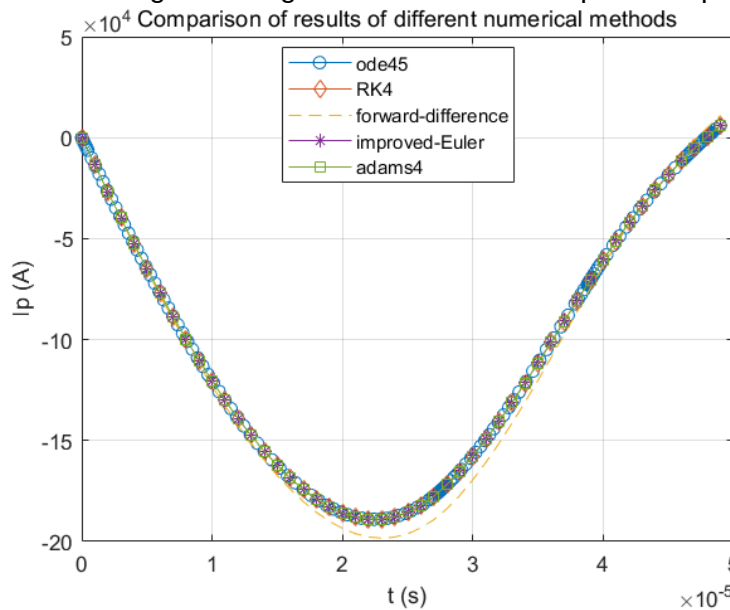


Figure 6 – Results of armature induced current (I_p) by different numerical methods.

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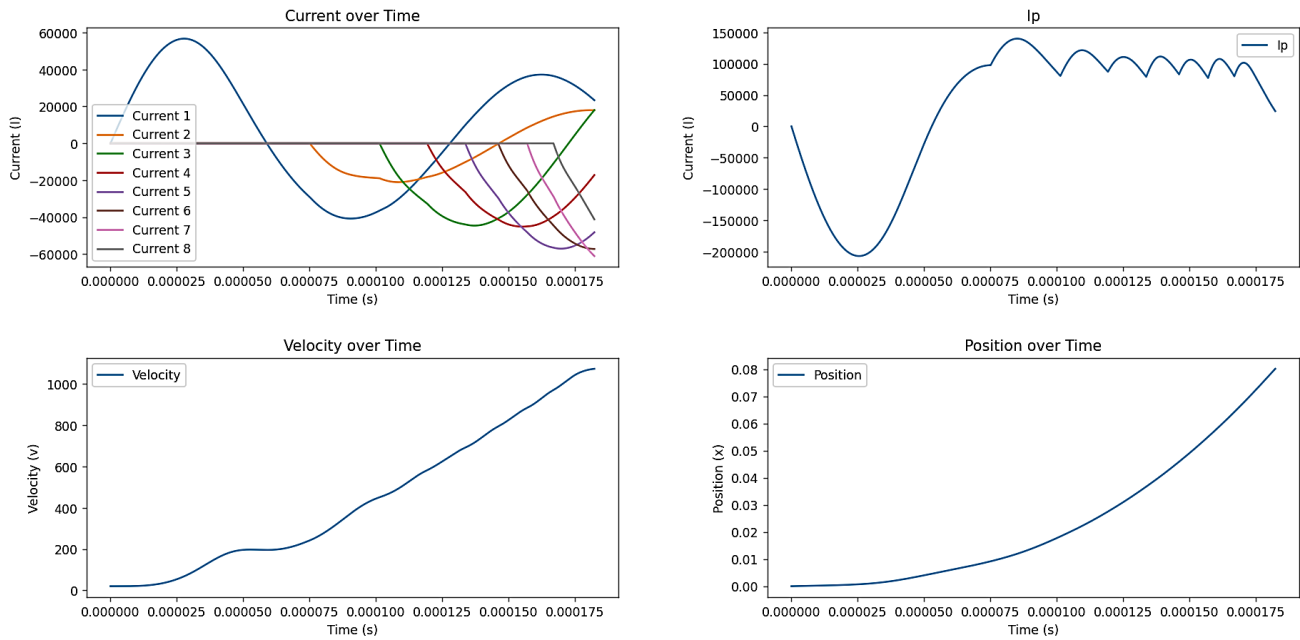


Figure 7 – Curves of an 8-stage coilgun launch, in which capacitors have a capacitance of $660\text{e-}6 \mu\text{F}$ and a charging voltage of 400 V.

3. Numerical Simulation of Electromagnetic Induction Coilgun

3.1 Numerical simulation of the coilgun

In the field of electromagnetic field analysis, the Finite Element Method (FEM) is widely used to handle complex electromagnetic problems. This method discretizes the problem into many small regions, thereby converting the complex electromagnetic field problem into a large matrix equation that can be solved numerically. In the field of engineering electromagnetic fields, ANSYS Maxwell software is widely recognized for its finite element analysis capabilities based on Maxwell's equations. Maxwell software can convert the complex electromagnetic field calculation equations into a finite element discrete form, thus performing well in terms of calculation accuracy and speed.

Kim et al. [5] studied the effect of projectile shape on the launching velocity of coilguns and conducted electromagnetic simulation analysis using Maxwell. Through this software, they analyzed the magnetic force and resistance coefficients of projectiles of different shapes in the electromagnetic field, optimized the design of projectile shapes to obtain the maximum magnetic force and minimum resistance. After the optimized design, projectiles of the best shape were manufactured, and their final launching velocity and performance were verified through experiments. Guo et al. [6] conducted a simulation study on the firing process of a multi-stage induction coil gun. They calculated the coupling relationship between the multi-stage thrust coil and the armature, as well as the temperature change of the armature during the launching process. By combining the motion equation of the armature, the velocity displacement characteristics of the projectile, the discharge current waveform, and the thrust waveform of each stage power module, the performance of the multi-stage coilgun was systematically analyzed.

This section applies ANSYS Maxwell software to conduct detailed simulation analysis on the induction coilgun, exploring its application potential and performance in practical engineering.

3.2 Verification of numerical simulation by theoretical model

In this study, the simulation of the 2-D magnetic field of the electromagnetic coilgun was carried out using Maxwell software. The general procedure involves geometric model construction, material definition, selection of boundary conditions, loading of excitation sources, setting solver options, and post-processing. For the transient magnetic field solver, in addition to current sources and current density sources, external circuit sources can also be applied. In this study, external circuit sources were used in the transient simulation of the coilgun. The driving circuit for the transient simulation was edited in Maxwell Circuit Editor. The transient magnetic field simulation model of the electromagnetic

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coilgun and the driving circuit are shown in Figs. 8 and 9. The model is symmetric about the Z-axis and mainly includes the aluminum projectile, the driving coil, the motion region, and the solution region. The aluminum projectile has an inner diameter of 10 mm, an outer diameter of 15 mm, a length of 20 mm, and one turn. The driving coil has an inner diameter of 20 mm, an outer diameter of 36 mm, a length of 30 mm, with a total of 60 turns. The initial position of the projectile is 15 mm, the initial velocity is 0 m/s and the mass is 5.3 g.

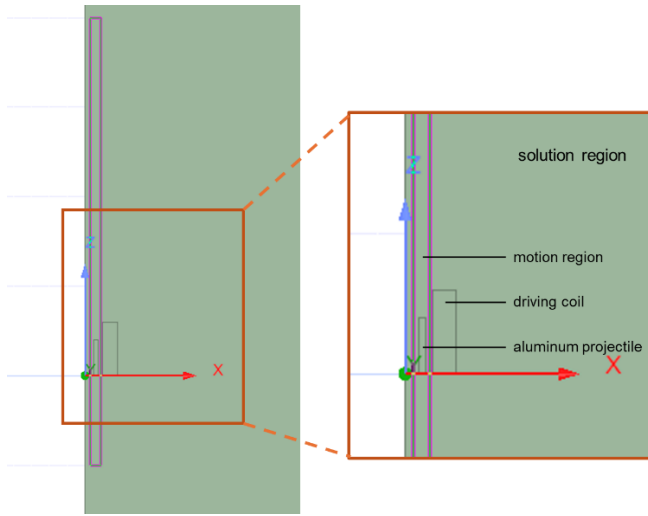


Figure 8 – The transient magnetic field simulation model

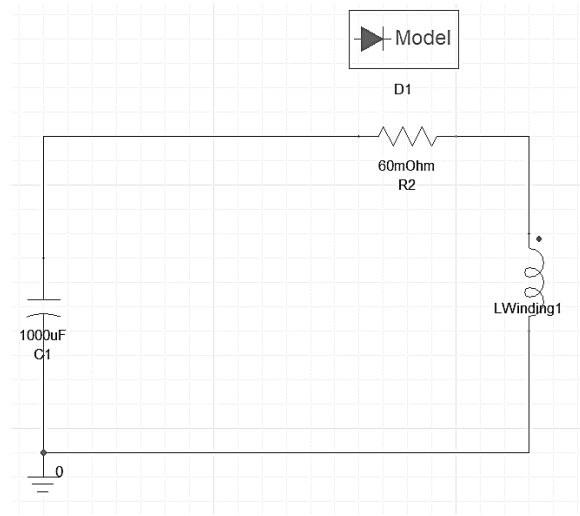


Figure 9 – The driving circuit

The speed change curve of the aluminum projectile, the current curve of the driving coil, and the voltage curve of the capacitor and obtained by Maxwell simulation and Python theoretical calculation are shown in Fig. 10 to Fig. 12. The accuracy of numerical simulation is verified by mathematical model.

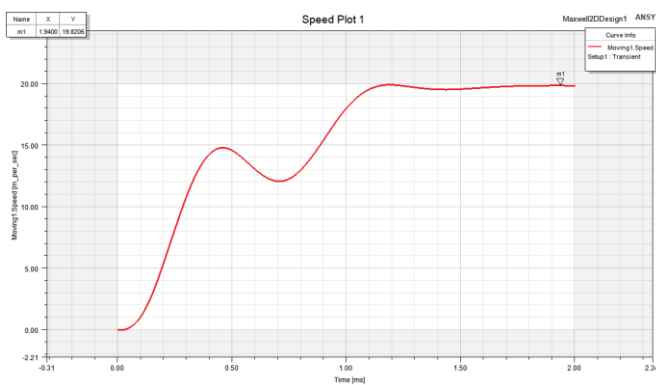


Figure 10 – The speed change curve of the aluminum projectile

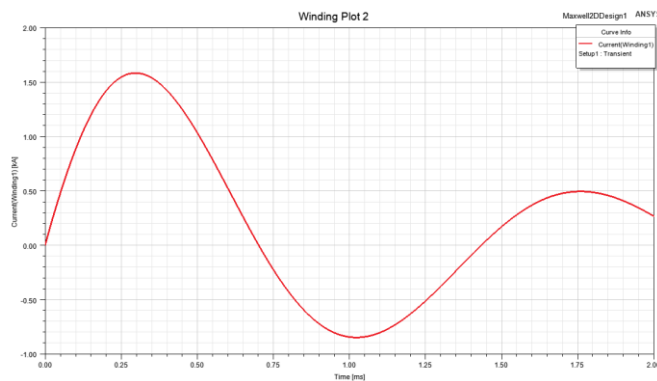
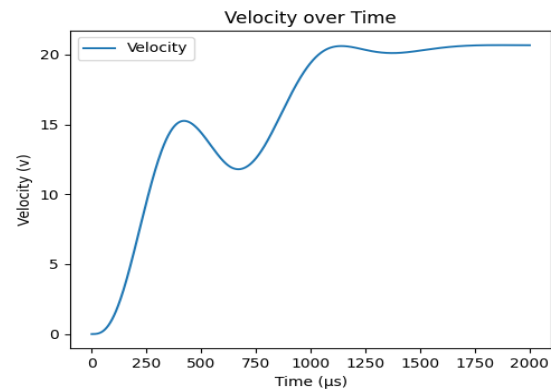
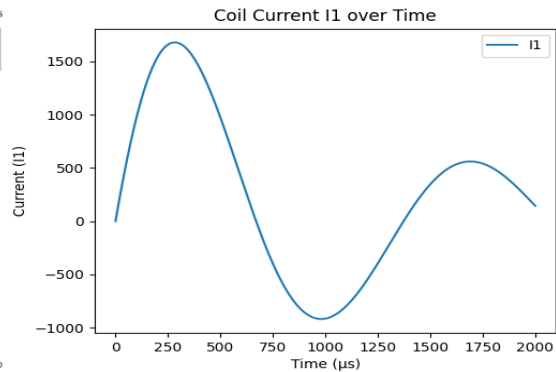


Figure 11 – The current curve of the driving coil



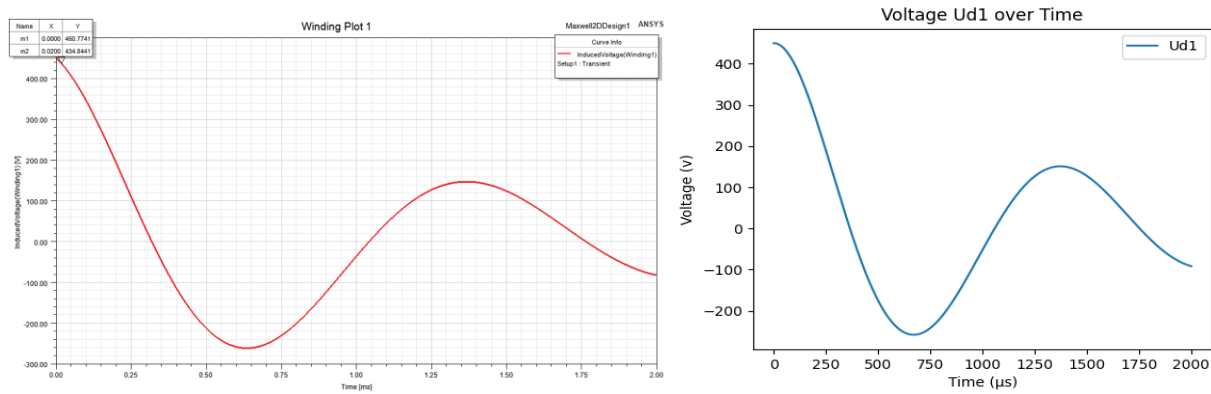


Figure 12 – The voltage curve of the capacitor

4. Conception of test

4.1 Scale test

A scaled 5-stage electromagnetic coilgun is built as shown in Fig. 13. The coilgun uses five stages of driving coils to accelerate the projectile. Each stage of acceleration system is mainly composed of solenoid coils, capacitors, photoelectric switches and resistors. The solenoid coils are made of 156 turns of copper wires, with a length of 28 mm, an outer diameter of 21 mm and an inner diameter of 8 mm. Each coil is powered by a capacitor with a capacity of $1000\ \mu\text{F} \sim 2000\ \mu\text{F}$, and a transformer raises the battery voltage of 12 V to 400 V to charge the capacitor. Photoelectric sensors are arranged between each stage of coils to accurately control the trigger time of the next coil. The projectile is an aluminum cylindrical projectile with a length of 290 mm and a diameter of 5 mm. The process of scaled coilgun launch of the projectile is collected by a high-speed camera, as shown in Fig. 14.



Figure 13 – A scaled 5-stage electromagnetic coilgun.

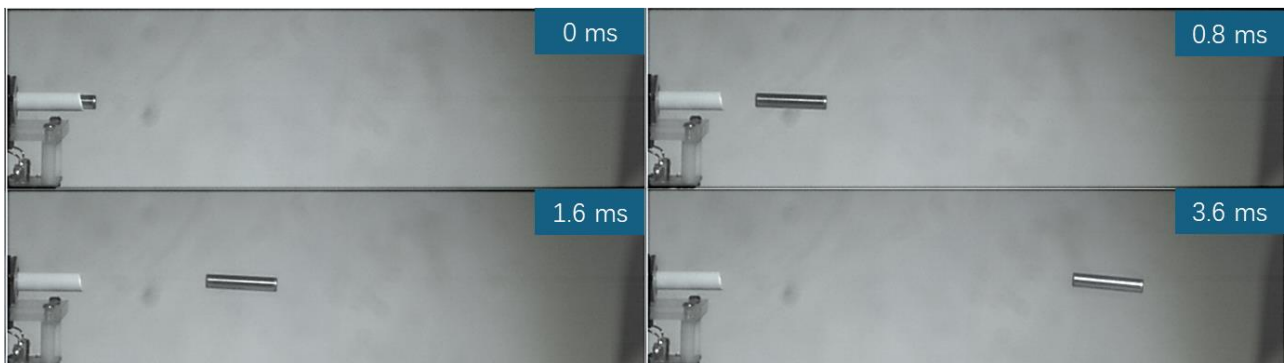


Figure 14 – The process of scaled coilgun launch of the projectile.

5. Conclusions and Prospect

This paper introduces a novel approach to ballistic impact testing utilizing electromagnetic launch technology. Initially, the principles underlying the electromagnetic induction coilgun are examined. A theoretical model is developed and subsequently solved using appropriate numerical methods. Following this, the electrical response of the coil and armature, as well as the dynamic behavior of the

projectile, are characterized. The electromagnetic launch model of the coilgun is then established and validated through simulations using ANSYS Maxwell. Building on these findings, a scaled testing framework is proposed, and a test conception is articulated. Ultimately, this work aims to develop a robust ballistic impact test scheme applicable at high temperatures, particularly for studying blade containment capabilities.

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