Research on a projectile-borne measuring apparatus for electromagnetic launcher

Ronggang Cao, Xueyi Hu, Erwa Dong, Xiao Ma and Yu Zhou

Science and Technology on Electromechanical Dynamic Control Laboratory, Beijing Institute of Technology, Beijing, China

1 E-mail: 3120190188@bit.edu.cn

Abstract. In order to evaluate the electromagnetic launch effectiveness and understand the corrosion damage of the electromagnetic launcher, it is necessary to master the magnetic field data in the bore. At present, there is no related research on the measurement of the bore magnetic field of the electromagnetic launcher. Therefore, a small-scale projectile-borne measuring apparatus based on B-dot probe is developed in this paper. This apparatus uses FPGA as the core. Through the static magnetic field measurement experiment, the data of the induced voltage and the induced magnetic field can be obtained. The projectile-borne magnetic field measuring apparatus designed in this paper can accurately measure the bore magnetic field of the electromagnetic launcher, which lays the foundation for further analysis of the influence of the electromagnetic field in the bore on the launch effect and investigation of the corrosion damage of the electromagnetic launcher.

1. Introduction

With the development of electromagnetic technology, electromagnetic launch technology has been developed rapidly [1-3]. Electromagnetic launch technology has the advantages of fast speed, long range, high precision, high power and low cost. The electromagnetic railgun is a new type of launch technology that uses electromagnetic energy to launch projectiles [4-5]. The electromagnetic railgun can increase the range of the artillery, shorten the flight time of the projectile and increase the lethality. In addition, electromagnetic launch technology can also be applied to other fields such as impact testing. In the future, electromagnetic launch technology may be used to launch small satellites into low earth orbit or even space at low cost [6].

During the launch of the electromagnetic railgun, the magnetic field generated by the high pulse current of the rail will not only interfere with the smart ammunition technology, but also cause eddy current loss in the rail and armature, which will damage the rail and armature. Therefore, it is necessary to measure and study the bore magnetic field of the electromagnetic railgun, which is the basis for studying the various phenomena that appear during the launch of the electromagnetic railgun. By measuring the magnetic field data of the electromagnetic railgun, a series of parameters such as rail current and armature speed can be calculated. This is an important means to study the damage of rail groove corrosion and evaluate the launch effect.

B-dot probe is a useful diagnostic instrument for analyzing the performance of electromagnetic launcher [7]. When the electromagnetic field changes, the B-dot probe will generate an induced voltage proportional to the time rate of change of magnetic flux. The experimental data measured by multiple fixed position B-dot probes can analyze the armature speed and current distribution [8-10].
These papers did not study the magnetic field conditions. Some researchers used probe signal integration to obtain the magnetic field strength to achieve armature magnetic field measurement [11]. In addition, Cao et al. [12] calculated the corresponding magnetic field based on the magnetic force measured during the start-up acceleration and separation phase to analyze the magnetic field at different positions and heights near the railgun. This mainly studied the external magnetic field of the electromagnetic railgun. At present, there is no related research on the measurement of the bore magnetic field of the electromagnetic launcher. Therefore, in order to realize the measurement of the magnetic field in the bore of the electromagnetic launcher, a small-scale projectile-borne measuring apparatus based on the B-dot probe is designed in this paper. This device obtains electromagnetic field information through the B-dot probe, controls and manages it through FPGA, and finally uses MATLAB to process the data. First, we introduce the main components of this device: mechanical part, protective part, hardware part. Then, we showed the process and results of the static magnetic field experiment. Finally, we use a standard field strength meter to calibrate the probe. Experiments have proved that this device can accurately measure the magnetic field of the electromagnetic launcher bore at low speeds.

2. System components
The magnetic field measurement of the induction coil is based on Faraday's law of electromagnetic induction. When the magnetic field density in the coil changes, an induced voltage is generated on the induction coil. The induced voltage generates a current in the coil proportional to the rate of change of the magnetic field. The sensitivity of the induction coil mainly depends on the permeability of the iron core, the area of the coil and the number of turns of the coil. Only when the magnetic field in the coil changes or the coil makes a cutting motion in the magnetic field, the induced voltage can be generated on the coil. Therefore, the induction coil cannot measure static or slowly changing magnetic fields. Induction coils are often used for close-range magnetic field measurement. The apparatus adopts a modular design and includes four modules: mechanical part, protective part, hardware part and software part.

The mechanical part is composed of the insulating shell of the measuring apparatus, and its main function is to carry the PCB board of the measuring system, the battery and the electromagnetic shielding body. The size and material of the insulating shell must meet strict requirements. First, the size of the insulating shell needs to be smaller than the size of the railgun bore. Secondly, in order to avoid the rail short circuit and damage to the measuring system, the insulating shell must use insulating and anti-overload materials. According to the size of the electromagnetic railgun, the cross-sectional size of the insulating shell is designed to be 19mm*39mm, and the length is designed to be 40mm.

The function of the protective part is anti-overload and electromagnetic shielding. The apparatus adopts potting technology for buffer protection, which can protect the launching direction from overload. The buffer material adopts epoxy resin material with good potting characteristics. It has the characteristics of strong adhesion, high strength and simple potting process. The curing shrinkage rate is generally 1%-2%. Therefore, the volume changes little after curing. Figure 1 shows the measuring apparatus after potting. Figure 2 shows the internal PCB diagram of the measuring device.

Figure 1. The measurement apparatus.
Figure 2. The PCB of the apparatus.
The electromagnetic shield body is embedded in the shell. In order to compare the electromagnetic shielding effectiveness of different materials, we simulated a variety of magnetic field shielding solutions. We select five points on the same plane for simulation calculation. Then we get the time domain curves of magnetic flux density of copper, aluminum, magnetic material and combined material shield respectively in Figure 3. The curves with different numbers represent the magnetic flux density at different locations. From Figure 3(a) and 3(b), it can be seen that the amplitude of the curve of copper shield is always lower than the amplitude of the curve of aluminum shield at the same position. The shielding effect of copper material is better than that of aluminum material. Comparing the four pictures in Figure 3, it can be seen that the magnetic flux density curve amplitude of the combined material shield is the lowest. Its shielding effect is the best among the four methods.

Hardware part includes the battery module, the analog-to-digital conversion module and the control module. Software part mainly refers to the timing control program of all hardware and the data processing program. Main functional blocks of apparatus are shown in Figure 4. The analog signal acquired by the B-dot probe is converted into a digital signal through the analog-to-digital conversion module. The core controller FPGA realizes the functions of data transmission, data storage and timing control. The battery module supplies power to the analog-to-digital conversion module and the core control module. Finally, the acquired magnetic field data is processed by MATLAB.
2.1 Battery and AD converter

The measuring apparatus designed in this paper needs to provide three power supply voltages of 7.4V, 3.3V and 1.5V. The 7.4V voltage is the external battery power supply voltage; the 3.3V voltage is provided by the ASM1117 voltage conversion chip, which is the supply voltage of the FPGA's VCCIO pin, 25MHz crystal oscillator, M25P40 external FLASH program memory and FRAM ferroelectric memory; the 1.5V voltage is the supply voltage of the VCCINT pin of the FPGA.

The change of magnetic flux in the B-dot probe coil will generate induced electromotive force. The device needs to send the digital signal of the measured induced electromotive force to the FPGA for processing. Since the signal measured by B-dot is an analog signal, the signal needs to be converted from analog to digital before it enters the processor.

According to the system design requirements, the AD chip selects the AD9280 from ADI (Analog Devices, Inc.). The AD9280 device is a single chip, 8-bit, 32MPS analog-to-digital converter (ADC). It uses a single power supply. It has an on-chip sample-and-hold amplifier and reference voltage source. It uses a multi-stage differential pipeline architecture. Its data rate reaches 32MSPS. Its power consumption is only 95mW. Its operating voltage range is +2.7V to +5.5V. Its differential nonlinearity error is 0.2LSB.

The reference voltage of AD9280 is 0~2V. If it exceeds the range, the converted digital value cannot be obtained. The electromotive force induced in the B-dot probe designed in this paper is between 2V and 10V. Therefore, the voltage needs to be transformed before the measured analog signal enters the AD chip.

2.2 Data storage

For the data measured by the probe, there are currently three main storage and transmission methods: local storage, wireless transmission and storage, and wired transmission and storage. The local storage method stores the probe measurement data in the local storage medium of the measurement system. This method is safe and reliable. Since data cannot be transmitted across the movement area of the projectile, a special pickup device is required. In addition, the device design should also consider the protection of the measurement system and storage medium. The wireless transmission storage method converts the probe measurement data into wireless signals such as optical signals and radio signals. The wireless signal is sent directly from the measurement system, and received and processed by the upper computer. This method can observe the processed data in real time, and there is no need to design a special pickup device. The strong magnetic field in the bore of the electromagnetic railgun may interfere with the wireless transmission signal and cause errors. The wired transmission storage mode transmits the probe measurement data to the upper computer through the extremely thin insulated twisted-pair signal wire. The signal transmission is stable and the anti-interference ability is strong. Because the signal line is thin and its bearing capacity is poor, this method cannot be used in high-speed launch experiments. Taking into account the diversity of the electromagnetic launch device structure, the power supply scale and the size of the transient current, this paper uses local storage for data storage.

The external memory is used to store the measured data. After the measurement device has collected the data, it needs to be connected to the computer to read out the stored data for the next calculation processing. There may be a power failure during data transmission, so the external memory chip needs to have the function of not losing data after power failure. This apparatus uses the FRAM.
as the storage chip, and the model is FM25L256. Its read and write speed can reach 20MHz. Its storage capacity is 256K.

2.3 FPGA
The control module is the core part of the measurement system. It controls the timing and logic of the remaining modules, and judges and processes the digital signals after AD conversion. The control chip we choose is FPGA, and its model is the EP1C3T100CN8 of cyclone I series. Compared with single-threaded MCU, this chip has powerful parallel processing capabilities. Its size and power consumption are greatly reduced. It improves the efficiency of measurement data processing. Due to its parallel processing characteristics, it can simultaneously manage and control the analog-to-digital conversion module, the internal FIFO buffer, the external memory, and the coordination work of other modules. Therefore, we choose FPGA as the main control chip, which can solve the shortcomings of customized circuits and overcome the shortcomings of the limited number of gate circuits of the original programmable devices. The control module has the characteristics of convenience, high speed, high reliability and short development cycle.

3. Experiment and results
The measuring apparatus proposed in this paper can measure the dynamic and static magnetic field in the bore of the electromagnetic rail-gun, and it can also measure the magnetic field in the case of projectile borne. Because the dynamic high-speed experiment is limited by the experimental conditions, we have carried out static magnetic field measurement experiments and obtained effective data under a low-speed condition through this apparatus.

In order to realize the measurement of the static magnetic field of the electromagnetic rail-gun, we use the electromagnetic railgun short-circuit device to conduct discharge experiments. In the experiment, we use a power supply composed of multiple capacitor pulse discharge modules. This power supply can regulate the discharge voltage and current. As shown in Figure 5, the rails of the electromagnetic railgun short-circuit device are 15mm wide and 40mm apart. In addition, the measuring apparatus is placed near the armature.

![Figure 5](image_url)

**Figure 5.** The relative position of the rail and the measuring device.

![Figure 6](image_url)

**Figure 6.** The induced voltage measured on voltage of 900V.

In order to prevent the excessive current in the short circuit device from causing the device to fly out of the rail, the experimental voltage is set to 900V. Because the experimental voltage and current are small, but the bore magnetic field has a linear relationship with the current, the bore magnetic field of the short-circuit device is correspondingly small. The induced magnetic field generated by the experimental device is small, which will be further reduced after passing through the voltage divider circuit. At the same time, the number of sampling bits of the AD chip is 8 bits, and the measured data has a small fluctuation range and low accuracy. Therefore, we have specially designed the voltage divider circuit to improve the accuracy of the measurement. Corresponding magnetic field data were measured at 900V experimental voltages. When firing at 900V, the probe is 85mm away from the armature. The number of turns of the B-dot probe at the front of the measurement system is 4 turns,
and the coil area is $64 \text{mm}^2$. The induced voltage data can be measured through experiments, and the measured magnetic field data can be obtained by further calculation.

**Figure 7.** The magnetic field curves on voltage of 900V.

**Figure 8.** The probe calibration.

Figure 6 shows the measured induced voltage. After calculation, the magnetic field curve can be obtained, as shown in Figure 7. It can be seen from Figure 6 and Figure 7 that there is a large fluctuation in the curve around 0.5ms. This is because the electromagnetic shielding effect of the measuring apparatus is not ideal enough, and the measuring system is still interfered by the electromagnetic field inside the electromagnetic railgun, resulting in a certain system measurement error. In addition, it is also because the electromagnetic field itself fluctuates during the launch process. Experiments have proved that this measuring apparatus can measure the static magnetic field of the electromagnetic railgun, and the dynamic measurement needs further experiments.

4. Calibration

According to the method of References [13-15], we use the standard field strength meter PMM-8053A to calibrate this apparatus. A large solenoid is used to offer the magnetic field. Add sinusoidal currents of different frequencies to the solenoid. Since the solenoid has sufficient height and size, the field in the center of the solenoid is considered to be approximately uniform. By comparing and analyzing the measured values of the PMM-8053A and the probe, the probe coefficient can be calibrated and a calibration curve can be obtained. From Figure 8, we can find that the measured values of the standard field strength meter and the B-dot probe are basically consistent under the low-frequency magnetic field condition. For this apparatus, the frequency band of the measurement signal is in the low frequency band. And the output voltage of the probe is equal to the magnitude of the induced electromotive force of the probe.

5. Conclusions

During the launch of the electromagnetic launcher, the high pulse current in the rail will generate a strong magnetic field, which is an important factor affecting the electromagnetic launch. In order to realize the bore magnetic field measurement of the electromagnetic rail-gun, a small-scale projectile-borne measuring apparatus based on B-dot probe is developed in this paper. The distance between the armature and the apparatus is invariant. This apparatus uses FPGA as the core to meet the requirements of data acquisition rate. The static experiments can prove that the apparatus can obtain effective magnetic field data in the condition of low speed. The projectile-borne magnetic field measuring apparatus measures the magnetic field inside the electromagnetic launcher, avoiding the magnetic field measurement error caused by the armature current. Through the standard field instrument calibration, this apparatus has the ability to accurately measure the magnetic field in the bore of the electromagnetic rail-gun. In the future, the transient launch mechanism of the electromagnetic launcher can be analyzed by simulation using the measured magnetic field data, which will lay the foundation for further analysis of the influence of the electromagnetic field in the bore on the launch effect and exploration of the corrosion damage of the electromagnetic launcher.
Acknowledgement
This work was supported by Science and Technology on Electromechanical Dynamic Control Laboratory, China, Beijing Institute of Technology, No. 6142601190605.

References
[1] Fair H D 2003 Electric launch science and technology in the United States IEEE Transactions on Magnetics 39(01) 11-17
[2] Fair H D 2007 Progress in Electromagnetic Launch Science and Technology IEEE Transactions on Magnetics 43(01) 93-98
[3] Fair H D 2013 Guest Editorial The Past, Present, and Future of Electromagnetic Launch Technology and the IEEE International EML Symposia IEEE Transactions on Plasma Science 41(05) 1024-27
[4] Ma W M and Lu J Y 2017 Thinking and Study of Electromagnetic Launch Technology IEEE Transactions on Plasma Science 45(07) 1071-77
[5] Li J, Yan P and Yan W Q 2014 Electromagnetic gun technology and its development High Voltage Engineering 40(04) 1052-64
[6] McNab I R 2019 Brief History of the EML Symposia: 1980–2018 IEEE Transactions on Plasma Science 47(05) 2136-42
[7] Evans B J and Smith L M 1991 A cross-correlation-based method for determining the position and velocity of a railgun plasma armature from B-dot probe signals IEEE Transactions on Plasma Science 19(05) 926-34
[8] Zhang G W, Cao R G and Li P 2018 Analysis of a Measurement Method for the Railgun Current and the Armature’s Speed and Initial Position IEEE Sensors Journal 18(23) 9526-33
[9] Wang Z J, et al. 2009 Evaluation of solid armature’s in-bore position, velocity, and current distribution using B-dot probes in railgun experiments IEEE Transactions on Magnetics 45(01) 485-89
[10] Zeng D L, Lu J Y, Cheng L and Zheng Y F 2019 A Novel Measurement Method of Solid Armature’s in-Bore Motion State Using B-Dot Probes for Rail Gun IEEE Transactions on Plasma Science 47(05) 2472-8
[11] Cao B, Ge X, Yang Y L, Li J X, Sun X C and Fan W 2014 Electromagnetic railgun armature magnetic field measurement and analysis based on B-Dot probe signal International Symposium on Electromagnetic Launch Technology (La Jolla, CA:IEEE) pp 1-6
[12] Cao R G, Duo Z and Su M 2019 Analysis of Magnetic Field Waveforms of Different Launching Stages of Rail Gun Based on Wavelet Transform IEEE Transactions on Plasma Science 47(01) 500-7
[13] Xie Y Z, Liu S K and Sun B Y 2004 Time domain and frequency domain calibration methods of electromagnetic pulse sensors and their equivalence Nuclear Electronics & Detection Technology 24(04) 395-9
[14] Cao R G, Zou J and Yuan J S 2009 Measurement and analysis of EMF around pulsed power supplies High Power Laser and Particle Beams 21(09) 1426-30
[15] Cao R G, Li J, Jiao Q J and Yuan J S 2013 Analysis and Measurement of Transient Currents in Railgun With Loop Probes IEEE Transactions on Plasma Science 41(05) 1479-83