AN INTEGRATED PLATFORM FOR SIMULATION, VALIDATION, ANALYSIS AND OPTIMIZATION OF ELECTROMAGNETIC RAILGUN SYSTEM

Yuchen Zhou^(a), Ping Ma^(b), Ming Yang^(c)

Control and Simulation Center, Harbin Institute of Technology Harbin, P. R. China

^(a) <u>zhouyuchen-01@163.com</u>, ^(b)<u>pingma@hit.edu.cn</u>, ^(c)<u>myang@hit.edu.cn</u>

ABSTRACT

There exist coupled mechanical, thermal, and electromagnetic diffusive processes with high-speed moving conductors in electromagnetic railgun (EMRG). Simulation can validate related theories and reduce physical experiments. Besides, post-simulation analysis reveals the influence of various uncertain factors on the system performance and supports the improvement of the system performance. The Electromagnetic launch technology advanced rapidly and it put forward higher requirements for the simulation tools. Thus, an integrated electromagnetic railgun simulation platform, which has multi-functions including simulation, model validation, post-simulation analysis and optimization, is needed urgently. Furthermore, the simulation platform should be capable of strengthening the management of simulation resources. An integrated EMRG simulation platform is designed and implemented consisted of HLA-based EMRG model, model validation tool, experimental design & data analysis tool and optimization tool. The application result shows that the platform can support the simulation, validation, analysis and optimization of EMRG simulation system.

Keywords: integrated simulation platform, electromagnetic railgun, model validation, optimization

1. INTRODUCTION

The electromagnetic railgun is a launcher using the Lorenz force to accelerate the projectile and consisted of Pulsed Power Supply (PPS), rail, armature and projectile. During the launching, PPS form a trapezoidal current pulse at megampere levels. Armature and rail work in extreme conditions. Furthermore, there exists ultra-high speed friction between rail and launch package. Meanwhile, mechanical, thermal and electromagnetic diffusive processes coupled intensely. Compared to the traditional guns, EMRG is characterize by faster response, higher damage effectiveness, lower demands for logistical support (Fair, 2007; Li, Yan and Yuan, 2014).

As the theoretical research of electromagnetic launch technology continuous improved, the EMRG model was built and simulation experiments were carried out on the computer model. Based on the post-simulation analysis, the structural parameters of electromagnetic railgun were optimized and engineering prototype was fabricated. The simulation model and theory can be examined and validated through physical tests. For the problems discovered in the experiments, theoretical research method, simulation method and prototype experiment approach can be combined to promote the development of electromagnetic launch technology.

Post-simulation analysis reveals the influence of various uncertain factors on the system performance and reduces the research and development (R&D) fund. Moreover, simulation can accelerate the EMRG research progress and improve the system performance and effectiveness significantly.

The Institute for Advanced Technology (IAT) designed and developed the EMAP3D program to solve the internal ballistics simulation of EMRG, which was a 3D Lagrangian finite element program for coupled mechanical, thermal, and electromagnetic diffusive processes with high-speed moving conductors (Hsieh, 1995). The EMAP3D code continues to be improved by introducing hybrid finite element–boundary element (FE-BE) algorithm (Hsieh, 2006) and developing novel split-domain iteration scheme to shorten the computation time(Hsieh and Thiagarajan, 2008; Tzeng and Hsieh, 2014).

Stephan Hundertmark in the French-German Research Institute of Saint-Louis (ISL) used the COMSOL program to set up a transient 3-D simulation of a small caliber railgun (Hundertmark and Roch, 2012). Furthermore, the muzzle velocity is compared to the experimental value and proved the validity of the simulation model under permissible error.

Antonino Musolino proposed a hybrid finite element method-method of moments (FEM-MOM) formulation capable of taking into account the velocity skin effect (Musolino, 2004). Nevsan Sengil applied the experimental design method to the EMRG simulation and some critical model parameters, like magnetic flux density and inductance gradient, were calculated through Monte Carlo method (Sengil, 2012).

As to the optimization of EMRG, the interaction between the launcher and pulsed power supply (PPS) system was studied and a numerical EMRG model powered by capacitor based PPS module was designed to find the optimal triggering configuration for a target muzzle velocity (Pitman, Ellis and Bernardes, 2014; Yan, Chao, Ma, Yang, Hu, 2014). The University of Texas at Austin Center for Electromechanics (UT-CEM) make great effort on the optimization of integrated launch package (ILP) (Kitzmiller and Driga, 2003; Kitzmiller, Pratap, Aanstoos, Cook, Kuenast, Murphy and Perkins, 1995).

Different methods or tools have been used to study the electromagnetic railgun simulation, analysis and optimization from various perspectives. The purpose of EMRG simulation research is to improve the system performance and provide decision support for the development of the engineering prototype. Thus, an integrated simulation platform is indispensable for the further study of electromagnetic launch technology.

Integrated simulation platform is a set of simulation model and support tools, which can support the calculation of simulation model and solution of a series of application problems (Henriksen, 1983; Cui, Xiao, Yang, Xie and Li, 2004). Besides, it can effectively manage the simulation model, algorithm, data and other simulation resources.

An integrated electromagnetic railgun simulation platform, which has multi-functions including EMRG simulation, EMRG model validation, post-simulation analysis, and simulation-based performance optimization, will play a significant role in the EMRG research.

Based on the EMRG model established in the literature (Ma, Yang and Hu, 2012) and the previous works on the EMRG model validation and optimization (Hu, Ma, Yang and Wang, 2012), the requirement of the integrated EMRG simulation platform is discussed and the architecture is designed; then, the detail design of the integrated simulation platform is proposed. Finally, the implantation and application of the platform are introduced to demonstrate that the platform can satisfy the demands.

2. DESIGN OF INTEGRATED EMRG SIMULATION PLATFORM

2.1. Requirement Analysis

Software requirement analysis is the first step in software design and it is critical to the success of simulation platform. As to the functional aspect of EMRG simulation platform, the calculation of EMRG model should be the primary function of simulation platform. The EMRG system model includes the internal ballistic model and exterior ballistic model.

Furthermore, to solve the problems encountered in the EMRG simulation, which include model validity, postsimulation analysis, and performance optimization, various supporting tools should be designed. These functions will be the primary functions of the integrated EMRG simulation platform.

• EMRG Simulation: simulate the accelerate process of projectile within the tube and the flight in the atmosphere.

- Model validation: provide suitable validation methods to analyse the similarity of the EMRG simulation data and test data.
- Experimental design: generate experimental design plan and save it to certain format which can be directly used by the EMRG simulation system.
- Post-simulation analysis: analyse the EMRG simulation data to discover the influence of uncertain factors on EMRG system.
- Performance optimization: optimize the discharge time series of capacitors and structural parameters to achieve better fire performance.

As to the structural aspect, the integrated EMRG simulation platform should have the ability to manage the simulation resources effectively for which we reference the partitioning design of OSI model. At the same time, to improve the reusability of the functional modules, the connections between different modules should be reduced. All the algorithms will be packaged to dynamic link library and data structure of the platform will be designed. The encapsulation of algorithms and reasonable design of data structure is the key to strengthen the independence of each module.

2.2. Architecture

For the reason that the integrated simulation platform has multiple functions and there is requirement for function expanding and software updating, it is necessary to design an extensible architecture. The architecture design should guarantee the reusability of simulation resources. The EMRG architecture is divided into Application Layer, Tools Layer, Resources Layer, and Infrastructure Layer.

- Application layer: the integrated simulation platform can satisfy the requirement of EMRG simulation, model validation, post-simulation analysis and simulation-based optimization.
- Tools layer: the integrated simulation platform consists of the HLA-based EMRG simulation system, model validation tool, experimental design & data analysis tool and optimization tool.
- Resources layer: the simulation resources can be managed effectively and reused easily in other software through resources layer. The projects, simulation data, algorithms and analysis reports will be saved to the designated database respectively.
- Infrastructure layer: the infrastructure layer includes the software and hardware which is essential to the establishing of the integrated simulation platform.

Application Layer	Simulation	Validation	Analysis	Optimization	
Tools Layer	HLA-based EMRG simu- lation system	Model Valiadation Tool	Experimental Design & Data Analysis Tool	Optimization Tool	
Resources Layer	Projects	Data	prithms Parameter	s Reports	
Infrastructure Layer	Operating System Soft	opment ware RTI	Network Communicatio n protocol	nputer Lan Network	

Figure 1. Integrated simulation platform architecture

The HLA-based EMRG simulation system has specially interface which allows to read the experimental design project and perform simulation experiment. The model validation tool and experimental design & data analysis tool can access the database to obtain the simulation data generated by the EMRG simulation system. The optimization tool calls the EMRG simulation model to accomplish the performance optimization.

2.3. Design of EMRG Simulation Model

The high-level architecture (HLA) is a standardized architecture for distributed simulation systems. The interactions in HLA-based simulation systems are managed by run-time infrastructure (RTI). This mechanism separates the simulation model development from run-time management and communication, which tremendously enhance the flexibility and extendibility of the simulation system.

The HLA-based EMRG simulation system is composed of electromagnetic railgun federate, target federate, detection federate, threat assessment federate console federate and data collection federate. The electromagnetic railgun federate includes the internal ballistic model and 6 degree-of-freedom (DOF) exterior ballistic model.

The console federate is designed to configure the model parameters and strengthen the simulation process management. The data collection federate can collect the data generated in the simulation and save it to the configured paths.

2.4. Design of Model Validation Tool

Simulation model validation is defined as determining that the model's output behavior has sufficient accuracy for the model's intended purpose over the domain of model's intended applicability (Sargent, 2009). The credibility of the EMRG model decides whether the simulation experiment result and the data analysis result can be accepted.

Data consistency analysis is a common approach to validate simulation model. The functions of model validation tool include data input, data consistency analysis and validation report generation.

According to the characteristic of EMRG simulation data, the validation tool provides Theil's inequality coefficient (TIC) and Grey Relational Analysis (GRA) for the data consistency analysis. TIC, firstly used to validate the missile systems (Naim, Willard, 1978), is an classical method providing insight into the validity of the EMRG simulation system.

The EMRG model validation includes the consistency analysis of discharge current, projectile velocity and projectile displacement. The discharge current is the most important evaluation index. The discharge current curve can be spitted into ascent stage, stable stage and decline stage and proper method should be chose to analyse each stage of the current curve with the aid of the validation tool.

2.5. Design of Experimental Design and Data Analysis Tool

There are numbers of uncertain factors in the EMRG model. Experimental design can be used to reduce the scale of simulation experiment in the studying of the influence of those factors on the simulation result. Multi-factors statistical methods provide a quantitative analysis method for the post-simulation analysis.

The functions of experimental design & data analysis tool include factors design, methods selection, experimental design table generation, and multi-factor analysis. There are three experimental design methods (Monte Carlo experimental design, uniform experimental design and orthogonal experimental design) and two multi-factor analysis methods (variance analysis and regression analysis). The experimental design table can be saved to the Access database or saved in XML format.

2.6. Design of Optimization Tool

The electromagnetic railgun launches projectile by the Lorenz force generated by the discharge current. Due to the drag is far less than the thrust, according to $F=L'I^2/2$, the stability of acceleration process mainly depends on the stability of discharge current. The stable current can reduce the damage to the rail, caused by high speed sliding contact between the armature and the rail.

Hu, Ma, Yang, Lu and Wang (2014) proposed a multistage optimization strategy based on improved particle swarm optimization (PSO) to optimize the discharge current form wave. The optimization tool realizes this algorithm using C++. Optimization tool function includes optimization index selection, constraint conditions setup and optimization.

3. IMPLEMENTATION AND APPLICATION

The EMRG simulation platform was developed with VC++ 6.0 and it works on a single computer installed windows operating system or on a distributed system composed of several computers. We illustrate the application of EMRG simulation platform.

Figure 2 shows the data visualization function of HLAbased EMRG simulation system and the dynamic curves displayed on the right are the capacitor discharge current curve and the total current curve. Then the GRA method is used to validate EMRG model and the data similarity analysis results proved that the model has a high credibility (Figure 3). As is shown in figure 4, variance analysis approach is used to study the uncertain factors' effects on firing accuracy. The uncertain factors include projectile mass, muzzle velocity and so on. Figure 5 shows the optimization of the discharge current curve.



Figure2 HLA-based EMRG simulation system

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Figure3 Model Validation Tool

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Figure4 Experimental Design and Data Analysis Tool



Figure 5 Optimization Tool

The simulation and analysis result shows that, the integrated simulation platform of electromagnetic railgun achieved the designated objective and can be used to the electromagnetic railgun simulation, validation, post-simulation analysis and optimization.

4. CONCLUSION AND FUTURE WORK

An integrated EMRG simulation platform consisted of a whole-trajectory model, model validation tool. experimental design & data analysis tool and optimization tool is designed and implemented. The application result indicates that the platform can support the EMRG simulation, validation, analysis and optimization. Due to the repeatability of simulation approach, the simulation experiments can replace the physical tests over the model's intended applicability domain. Therefore, the simulation method can and accelerate the research development of electromagnetic launch technology.

Presently, the study of EMRG optimization has been concentrated on the optimization of the discharge sequence to obtain higher muzzle velocity, which is still a constrained single objective optimization. Actually, the efficiency of the PPS in continues firing should not be ignored. Thus, the constrained multi-objective optimization of the current will be considered. The tools of Integrated EMRG Simulation Platform are so loosely integrated that we plan to extend the platform to a more flexible development environment.

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AUTHORS BIOGRAPHY

Yuchen Zhou is a Ph.D. student at Harbin Institute of Technology (HIT). His research interests include simulation system evaluation and optimization. His email is zhouyuchen-01@163.com.

Ping Ma a professor of control and simulation center at HIT. Her research interests include system simulation theory and simulation system optimization. Her email is pingma@hit.edu.cn.

Ming Yang is the corresponding author. He is a professor and the director of control and simulation center at HIT. His research interests include system simulation theory and VV&A. His email is myang@hit.edu.cn.