Design of Firing Impulse Simulator and Analysis of Its Key Research and Development Technologies

Chi He[1], Guangling Dong[2,3], Hongquan Wu[3], Qiang Li[3] and Kun Lu[3]
[1]*School of Mechatronic Engineering, CUST, 7089 Weixing Road, Changchun, China*
[2]*School of Astronautics, Harbin Institute of Technology, 92 Xidazhijie Street, Harbin, China*
[3]*Department of Test Technology, Baicheng Ordnance Test Center of China, Mailbox 108, Baicheng, China*

Keywords: Weapon System, Approval Test, Firing Impulse Simulator, Impulse Waveform Simulation, Key Technology.

Abstract: A key technology problem with respect to approval testing is that of simulating firing impulse in large calibre weapon systems without firing live ammunition with many problems as high cost, strict environmental conditions, large numbers of staffing, wide test field, etc. There are two main methods in use at present: the first method is to carry out numerical simulation of gun firing dynamics with modelling and simulation (M&S) technology; the second method is to conduct hardware-in-the-loop simulation test with firing impulse simulator (FIS). The latter types of methods generate impulse effect to simulate gun live firing from power sources of gunpowder, gas, or liquid. FIS with gunpowder or gas as power source take on problems as low control precision, complicated operating process, and poor safety. In this paper, a FIS which transfer test data via CAN (Control Area Net) bus was designed and developed. System composition and working principle are introduced based on analyzing features of similar products, where key technologies as counter-recoil analysis, mass and speed choice of pounding head, system safety design are studied with emphasis. The research results indicate that FIS can be used as an effective supplementary to live firing in approval test of weapon system.

1 INTRODUCTION

Operational requirements in future wars are making newer and higher requests on gun weapon system. Constitutes of modern gun is growing more complex with higher technology integration level, which make the utilization of new theory, technology and materials become an inexorable trend. Improvement in overall operational effectiveness of gun increases the cost of development and tests rapidly, which also causes a longer and longer deployment cycle. In order to solve this problem, it has become an inevitable tendency to change the traditional mode of "manual design to trial-manufacture to test validation" with new techniques of simulation, computer and experimental testing, which also improves development level, shortens development cycle and saves life cycle expense.

Simulation technology has been used widely in development and test fields of gun weapon system at present. The U.S. Army is also applying advanced simulation technologies, real-time data-sharing processes and communication architectures to be able to test multiple weapon systems from different locations, simultaneously. To make that possible, the Army's Developmental Test Command is focusing on "virtual proving ground" technologies, which rely on modelling and simulation to create realistic testing environments (Cast, 2001). The FIS can simulate the recoil, trunnion loads and ballistic shock effects for tank and howitzer cannons. Thus, it can be used to check mechanical structure strength of weapon system and electrical system reliability, examine mechanism action, stress-strain in critical parts of gun carriage, transient response for recoil and counter-recoil of gun, and inspect the operational reliability of recoil mechanism, dependability of trunnion, electrical apparatus, and other accessories (Sanders and Patenaude, 1996).

In the field of gun firing impulse simulation technology, experts and scholars focus mainly on four aspects. The first is utilization and effectiveness study on gun firing impulse simulation, such as research report from the U.S. army Aberdeen test

He C., Dong G., Wu H., Li Q. and Lu K..
Design of Firing Impulse Simulator and Analysis of Its Key Research and Development Technologies.
DOI: 10.5220/0005511604530460
In *Proceedings of the 5th International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (SIMULTECH-2015), pages 453-460
ISBN: 978-989-758-120-5

center "Army Combat Systems Test Activity - Best Manufacturing Practices" (Aberdeen Test Center, 1994) analyzed the economic efficiency of FIS. James G. Faller (1997) from Army test and evaluation command of APD analyzed the convenience of using FIS. The second is design research on FIS, such as Lang (2012) developed a shooting simulation device for multi types of launcher, which could adjust loading attitude and strength according to launcher type. The third is testing technology study on key parameters of recoil mechanism , such as Zhao (2003) realized measurements for parameters as working pressure and recoil resistance of recoil mechanism. The fourth is key technology study on simulator design and numerical simulation. Professor Yao (2001) and Dr. Di (2012a) introduced the basic principle of gun recoil simulation test system, and built numerical simulation model of recoil dynamics with combined calculation of gun recoil and interior ballistic according to system features, where two different types of gun are simulated to realize dynamics simulation of recoil and counter recoil. Dr. Di (2012b) established mechanical model and nonlinear model of bumper, and calculated its kinematic equation with fourth-order Runge-Kutta method in Matlab, which is used to analyze the influences of impulse mass, impulse speed, bumper linear rigidity, nonlinear rigidity, and damp on recoil acceleration of gun barrels. This research provided theoretical basis for development of gun simulation test mechanism.

In this paper, we mainly carry out three studies; the first is on implementation of FIS, where composition and working principle of controllable hydraulic technology based FIS are introduced. The second is on analyzing key techniques in developing of FIS. The third is about simulated effect validation of FIS with live firing results. In this way, practical application problems of simulation in test and evaluation of gun are solved.

2 SYSTEM DESIGN OF FIS

2.1 Implementation of FIS

2.1.1 FIS with Gunpowder Power Source

Simulation test system is composed of impulse generator (1), centering mechanism (2) and pedestal (3). Its structural representation is shown in Figure 1.

As the kernel component of simulation test

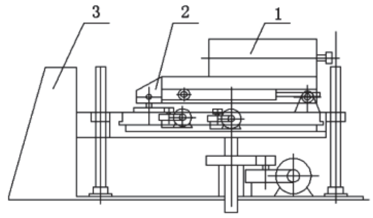

Figure 1: Structural representation of simulation test system.

and piston, which takes on the function of simulating system, impulse generator is composed of noumenon gunpowder gas pressure of interior barrel at live firing, and provides motive force of recoil motion for gun under test. Centering mechanism guarantees exact alignment of impulse generator piston axis and gun-bore axis for reliable, safe, and stable recoil motion.

As the support platform of simulation test system, pedestal bears the gravity of testing machine and resistance to recoil. Impulse generator takes on elastic fixing instead of rigid connection to pedestal via a suit of counter recoil mechanism, which provides elastic and brake force for recoil part of impulse generator.

Working principle of impulse generator is shown in Figure 2 (Gao et al, 2014). It is similar to general gun weapon system except the loaded informal pills of blank ammunition with minor-caliber and little dosage, which fires the recoil part of gun instead of standard ammunition.

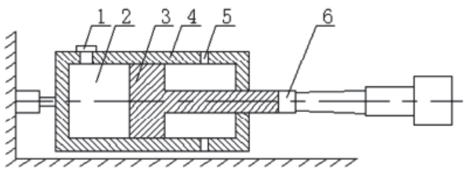

Figure 2: Working principle of impulse generator.

In simulation firing test, firing device (1) ignites gunpowder in combustor (2) first. Then, the generated propellant gas pushes piston component (3) to drive the motion of gun muzzle (6) connected on the other end of piston rod, which realizes the recoil motion of gun in test. When the front face of piston moves to vent hole (5) on noumenon, powder gas is exhausted to atmosphere, which decreases pressure rapidly. The driving force on piston component drops down and stops motion by resistance to realize separation from gun muzzle. After that, recoil part of gun in test proceeds with inertial recoil and counter recoil motion. On the other hand, recoil part of impulse generator is driven to the opposite direction by pressure of propellant gas, whose buffer and reset are realized through combined action of its recoil apparatus and recuperator.

2.1.2 FIS with Power Source from Strikes of High Speed Mass Block

As hydraulic power transmission is an easy way to realize automatic control of high precision movement with heavy load, it is often adopted as power source of FIS. Composition diagram of simulation test device is shown in Figure 3 (Liu et al, 2011).

The test device is mainly composed of hydraulic power subsystem and impulse subsystem. Where,

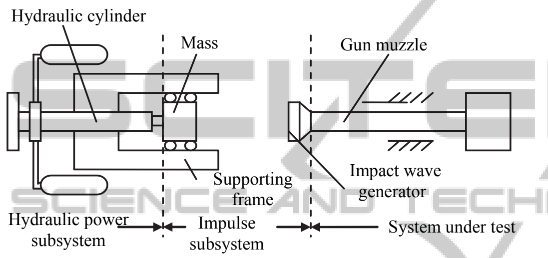

Figure 3: Diagrammatic sketch of simulating test facility.

hydraulic power subsystem takes on the effect of generating major flow rate in a short time, hydraulic cylinder drives mass block to move with high speed. At certain speed, piston rod and load would separate. Impulse subsystem is composed of mass block and bumper, which transmits kinetic energy to recoil part via strikes of mass block and muzzle bumper. In this way, it provides energy for recoil motion of gun. Then, mass block reset under the effect of return device for next strike. The purpose of above program is to realize strong transient impulse, which is centered on by subsystem designing.

2.1.3 FIS in Aberdeen Test Center of U.S. Army

In 1990s, dynamic simulation test device of gun has been used in Aberdeen test center of U.S. army in test and approval process of main battle tank type M1A2, which took full advantage of simulation test technology, just as shown in Figure 4 (Aberdeen Test Center, 2010).

Compared with live firing test, simulated firing with dynamic simulation test device saved over 20 million dollars in the same year. Therefore, U.S. military standard MIL-M-45976 stipulates clearly that “Simulator can be used to carry out test and evaluation”.

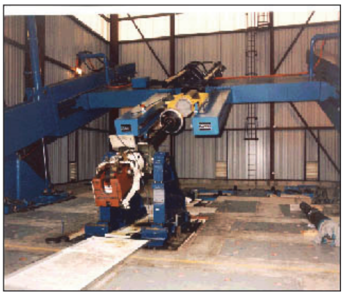

Figure 4: FIS of Aberdeen Proving Ground U.S. army.

The system takes on the following features (Aberdeen Test Center, 2010):

- Facility for testing the mechanical and hydraulic components (recoil systems, bearings, seals, etc.) of large caliber weapon systems without firing live ammunition;
- Inputs a repeatable force (up to 3 million pounds-force) to the system under test to replicate actual and projected firing loads at elevation from 0° to 85°;
- Can be used to conduct life cycle wear, fatigue, and reliability, availability, maintainability and durability (RAM-D) tests of weapon systems or cannon and recoil on a test mount;
- Rate-of-fire is dependent upon the impulse level and test item mounting configuration;
- The FIS is also applicable to shock/impulse tests of mounted electrical components, isolation mounts, and shock absorption systems;
- Indoor facility reduces test costs and environmental impulse, and eliminates weather delays;
- On-site 32-channel analog and digital Data Acquisition System is expandable to meet any test requirement.

2.2 System Composition and Working Principle of FIS

2.2.1 System Composition

FIS is designed as a distributed control and measuring system based on CAN bus, which is mainly composed of the following four parts: (1) dynamic simulation mechanism; (2) bearing system of power mechanism; (3) performance parameter testing end of gun; (4) hydraulic power source. Dynamic simulation mechanism is shown in Figure 5. Where, dotted line box indicates power source; solid double lines are hydraulic pipeline connection; bold solid double line arrows represent nonrigid connection.

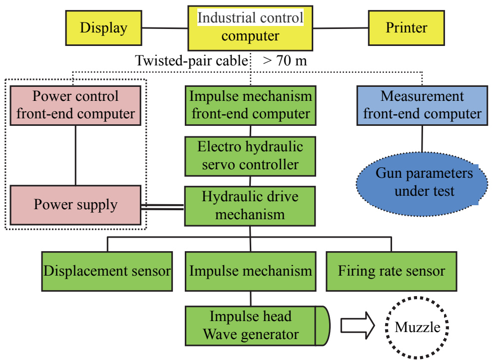

Figure 5: FIS system function block diagram.

2.2.2 Principle of Impulse Effect

There are many impulse generation types as explosion, gravity, acceleration, electrical driven, hydraulic pressure, etc. In this design, hydraulic power source is adopted, which uses momentum transfer principle to simulate firing impulse of gun. The impulse blow process is shown in Figure 6.

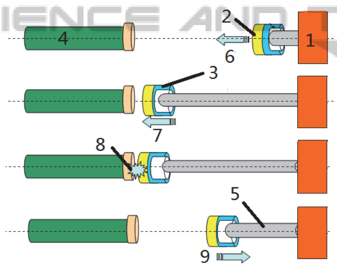

Figure 6: Principle of muzzle impulse procedure.

As velocity generator (1) accelerates (6) impulse head (3) to certain speed, impulse head separates (7) from speed generator. Then, waveform generator (2) set between gun muzzle (4) and impulse blow head forms strikes on gun muzzle. In collision process, transmission of pounding head momenta to gun forms strong impulse force and acceleration. Where, control on impulse blow waveform, impulse width, impulse force and impulse acceleration could be realized through modulating the stiffness of waveform generator. After impulse, recovery device (5) of pounding head retrieves impulse head (9), and prepares for next impulse test.

3 ANALYSIS ON KEY TECHNIQUES

3.1 Analysis of Counter Recoil Force

Firing dynamics simulation with gun impulse simulation test technology is a feasible way for repeated examination on counter recoil mechanism. As counter recoil mechanism constitutes the core component of gun, its comprehensive evaluation improves safety factor in operation. Forces on counter recoil mechanism determine forces imposed on gun carriage, performance parameters of counter recoil mechanism, and firing stability, etc. Therefore, working conditions of counter recoil mechanism determine the forces conditions on gun. Recoil motion equation is shown in Equation (1).

$$M_h \frac{\mathrm{d}W}{\mathrm{d}t} = F_{\mathrm{pt}} - F_{\mathrm{R}} \tag{1}$$

Variable substitution of t to x in Equation (1) is made to research relationship between recoil resistance F_{R} and recoil length λ, we get

$$\frac{\mathrm{d}W}{\mathrm{d}t} = \frac{\mathrm{d}W}{\mathrm{d}x}\frac{\mathrm{d}x}{\mathrm{d}t} = W\frac{\mathrm{d}W}{\mathrm{d}x} \tag{2}$$

According to equation (2), we have

$$M_h W \frac{\mathrm{d}W}{\mathrm{d}x} = F_{\mathrm{pt}} - F_{\mathrm{R}} \tag{3}$$

Integrating Equation (4) from the start of free recoil to any route point x,

$$\begin{aligned} M_h \int_0^W W\mathrm{d}W &= \int_0^x F_{\mathrm{pt}}\mathrm{d}x - \int_0^x F_{\mathrm{R}}\mathrm{d}x \\ \frac{1}{2} M_h W^2 &= \int_0^x F_{\mathrm{pt}}\mathrm{d}x - \int_0^x F_{\mathrm{R}}\mathrm{d}x \end{aligned} \tag{4}$$

At the end of recoil motion, we have $x = \lambda$, $W = 0$, so

$$\int_0^{\lambda} F_{\mathrm{pt}}\mathrm{d}x - \int_0^{\lambda} F_{\mathrm{R}}\mathrm{d}x = 0 \tag{5}$$

Generally, route λ at the end of recoil motion is far larger than route x_{0k} at after effect time. Namely, at the end of after effect time, recoil motion would continue instead of stop. Yet recoil force F_{pt} vanishes after x_{0k}. So the upper limit λ of integration in above equation for F_{pt} could be substituted by x_{0k}, with result unchanged.

$$\int_0^{x_{0k}} F_{\mathrm{pt}}\mathrm{d}x = \int_0^{\lambda} F_{\mathrm{R}}\mathrm{d}x \tag{6}$$

This equation shows such a conception that the total power of recoil forces on recoil part equals to that of resistance to recoil. Let

$$\overline{F}_{\mathrm{R}} = \int_0^{\lambda} F_{\mathrm{R}}\mathrm{d}x / \lambda \tag{7}$$

$\overline{F}_{\mathrm{R}}$ is mean resistance, namely the integral mean value along the whole recoil length λ, which can also be expressed as:

$$\lambda = \int_0^{\lambda} F_{\mathrm{R}} \mathrm{d}x / \bar{F}_{\mathrm{R}} \tag{8}$$

If the total power $\int_0^{\lambda} F_{\mathrm{R}} \mathrm{d}x$ of resistance to recoil is a constant, the relationship between resistance to recoil and recoil length can easily be seen from above equation. Namely, as $\bar{F}_{\mathrm{R}}$ increase, λ decreases; as $\bar{F}_{\mathrm{R}}$ decrease, λ increase. Yet the total power $\int_0^{x_k} F_{\mathrm{pt}} \mathrm{d}x$ of recoil force is variable, total power of resistance to recoil $\int_0^{\lambda} F_{\mathrm{R}} \mathrm{d}x$ is not a constant. It can be described as follows: suppose the resistance to recoil $F_{\mathrm{R}} = F_{\mathrm{pt}}$, then recoil part would not recoil, namely $x_{\mathrm{K}} = 0$, total power $\int_0^{x_k} F_{\mathrm{pt}} \mathrm{d}x$ equals to zero; if $F_{\mathrm{R}} = 0$, i.e. recoil motion is realized under free recoil conditions, the route at the end of ulterior period is x_{0k}, the total power would be $\int_0^{x_{0k}} F_{\mathrm{pt}} \mathrm{d}x$, without doubt we can get a maximal total power at this moment. In this way, total power of recoil force on recoil part changes with resistance to recoil. Generally, the selected resistance to recoil F_{R} is much less than recoil force F_{pt}. Therefore, total power is close to integral value $\int_0^{x_{0k}} F_{\mathrm{pt}} \mathrm{d}x_0$, whereas $\int_0^{x_{0k}} F_{\mathrm{pt}} \mathrm{d}x_0 = \frac{1}{2} M_h W_{0k}^2$.

According to the analysis above, counter recoil mechanism works as a kinetic energy absorption device for free recoil motion. While firing on gun carriage, the total power of recoil force to gun is equal to that of resistance to recoil, and is approximately the same size as maximal free recoil kinetic energy. As long as the shooting momenta (or impulse) on recoil part of gun can be simulated with firing impulse simulation test technology, the same recoil motion characteristics as living firing for recoil part of gun can be generated, which mainly include parameters as recoil route length, recoil velocity, acceleration (recoil kinetic energy), recoil and counter recoil time, maximal resistance to recoil and work of resistance, etc.

3.2 Confirmation on Mass and Speed of Impulse Head

According to impact working principle, as impulse head is accelerated to certain initial speed v_1 to impact on gun in test along specified axis direction, analysis on axis direction can be simplified as shown in Figure 7.

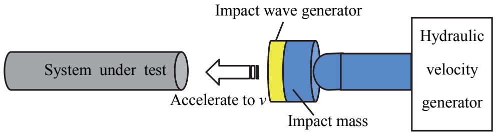

Figure 7: The principle diagram of FIS.

Suppose shock pulse generator and recoiling part take on mass of m_1 and m_2 respectively, their impact happens along axis direction. In the shocking process, shock pulse generator transmits the momenta to recoiling part, and generates corresponding impact impulse load. As the internal force in collision process is far larger than external force, momentum conservation theorem can be used for the system composed of these two parts along axis direction. Thus, we get Equation (9). The obtained impact momenta P_2 of recoiling part is gotten from required integration of impulse load.

$$m_1 \cdot v_1 = m_1 \cdot v_1' + P_2 \tag{9}$$

Where, m_1 is mass of shock pulse generator; v_1 is initial impact speed of shock pulse generator; v_1' is residual impact speed of shock pulse generator; P_2 is the obtained impact momenta of recoiling part.

Using conservation of energy theorem to system composed of shock pulse generator and recoiling part before and after impact. As leading end of shock pulse generator is a stiffness tunable elastic impact programmer, and back end of recoiling part is impact cushioning device, their impact is a non-perfect elastic collision existing kinetic energy rejection E'. According to conservation of energy theorem, we get Equation (10). The obtained kinetic energy E_2 from impact is determined by impact impulse loading curve.

$$\frac{1}{2} m_1 \cdot v_1^2 = \frac{1}{2} m_1 \cdot v_1'^2 + E_2 + E' \tag{10}$$

Where, E_2 is the obtained energy after impact loading on recoiling part; E' is the lost kinetic energy in collision process.

Suppose the ratio of specific energy loss to obtained impact energy of recoiling part is α. Reorganizing Equation (9) and (10), we get Equation (11) and (12).

$$m_1 \cdot (v_1 - v_1') = P_2 \tag{11}$$

$$m_1 \cdot (v_1 + v_1') \cdot (v_1 - v_1') = 2 \cdot (1 + \alpha) E_2 \tag{12}$$

Suppose the ratio of residual speed and initial speed of shock pulse generator is β, we can get Equation (13) and (14) from Equation (11) and (12).

$$v_1 = \frac{2(1+\alpha)E_2}{(1+\beta)P_2} \tag{13}$$

$$m_1 = \frac{P_2^2}{2(1+\alpha)E_2}\left(\frac{2}{1-\beta}-1\right) \tag{14}$$

For definite impact mission, the required impulse waveform can be obtained by modulating impact programmer after making clear shock pulse generator mass m_1 and initial speed v_1. In addition, relevant impact impulse P_2 and E_2 are confirmed for certain corresponding energy ratio α.

Shock pulse generator mass m_1 should be confirmed first. On occasions of guaranteeing impact impulse, increase in m_1 would reduce the requirement of initial speed v_1. As such, m1 should be as large as possible. On the other hand, over size of m1 could result in large residual speed of shock pulse generator, which influences the effective transmission of energy. Besides, large residual speed would increase requirements on buffer and braking system. Therefore, system design should guarantee the residual speed be within 10%, i.e. β is no bigger than 0.1.

From the above two principles, taking β in equation (14), we can get m_1.

$$m_1 = 0.61 \cdot \frac{P_2^2}{(1+\alpha)\cdot E_2} \tag{15}$$

Secondly, initial speed v_1 of shock pulse generator is determined. Based on the given mass of shock pulse generator, we can see from equation (11) that initial speed is determined by impact momenta P_2 of recoiling part in test. While taking $\beta = 0.1$, we can get v_1.

3.3 Research on Security Protection Problem

Security protection of FIS is an important problem, where passive protective layers as non-interference physical construction, adequate component strength, rational hydraulic and mechanical buffer guarantee the security of FIS from bottommost level.

Security design for driving system of speed generator provides basic safeguard and means for security protection of system, which is active executor of protection actions.

Hardware and software protect of control system are uppermost protective layer for ultimate realization of active protection strategy.

3.3.1 Mechanical System

In working process of FIS, it is required to guarantee that no mechanical impacts between mechanical part and actuating mechanism happen. Rational design requirements and criteria for each component of FIS are given out based on analysis of stressed state, which gives out detailed calculation of strength, stiffness, longevity, etc. and retains high enough safety system and proper design allowance. To prevent component damage in impact process, mechanical cushioning device of shock pulse generator need to be designed for residual energy absorption of shock pulse generator. In this way, impact effect on other components is reduced effectively, which further ensures the safety, reliability and long-time running of FIS.

3.3.2 Safeguard of Driving System

Driving system is both operative part of FIS and specific safeguards executor. In order to guarantee the safe operation of FIS, security protection function is designed for hydraulic driving system. Protection mode shown in Figure 9 can be adopted in design of driving system, i.e. locking valve is used to lock driving system on certain location when system failures occur.

3.3.3 Safeguard of Loading System

When system failures appear, automatic switch from loading control to position control is realized to keep the system in the current position, which avoids further damage on equipment. While control system problem makes positioning safeguard unachievable, the system links up cavity A and cavity B of hydro-cylinder, thus the forces exerted on system in test approaches zero, which realizes safeguard function.

3.3.4 Safeguard of Control System

The following measures can be adopted for hardware protection of control system:

- Monitoring and alarm of lines: main lines including control and power supply loops as control element, driven element, sensors, etc. are monitored at real time. Once open wire or plug loosening state is detected, protective treatment can be proceeded in time by control system;
- Millisecond level monitoring plant of computer failure: millisecond level computer failure monitoring plant (also called watchdog) could detect running status of real-time controller in

real time. Once failure or system halted appears on real-time controller, system control would be taken over by watchdog. Then, security protection process is triggered to realize security protection of system.

4 EXPERIMENTAL VALIDATION

4.1 Technical Specification of FIS

Technical specifications mainly include: maximal recoil driving force, force cell precision, angle range, adapting initial height, forward and astern speed, maximal route, hydraulic cylinder retraction speed, forward positioning error, positioning holding time, tacho-generator precision, impact frequency, simulation precision, performance parameter measuring accuracy, etc.

- Maximal recoil force: no less than 4000kN;
- Force cell precision: no less than 0.5%;
- Angle range: 0°-45°;
- Adapting firing line altitude: 500mm-2000mm;
- Impulse velocity: 10m/s (adjustable with program);
- Hydraulic cylinder rapid retraction speed: 0.1m/s;
- Forward positioning error: ±5mm;
- Impact frequency: impulses up to 2-3 rounds per minute;
- Performance parameter measuring accuracy: superior to 1% F.S.

In order to check if impact test data of FIS satisfies requirements of system design, its key parameters need to be validated by actual test. Key technical indexes of firing impact test model include duration of shock pulse, impact force, impulse, impact acceleration peak value, continual impact number, impact speed, angle regulating range, etc. In this paper, we give out validation results of three major parameters as impulse duration, impact force and impulse.

4.2 Comparison Validation Test with Live Firing

Take live firing test data of certain shrapnel as truth value, live firing impact (resultant force in gun bore) curve is built. Three simulation impact tests of this gun are carried out with FIS, correlation curves of three simulated impact to live shrapnel are shown in Figure 8 and 9.

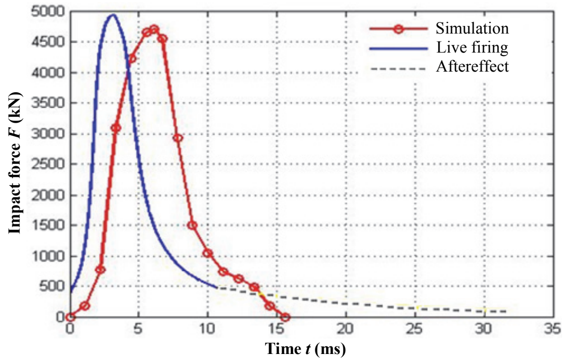

Figure 8: Contrast curve of a howitzer live firing with 1st simulation firing.

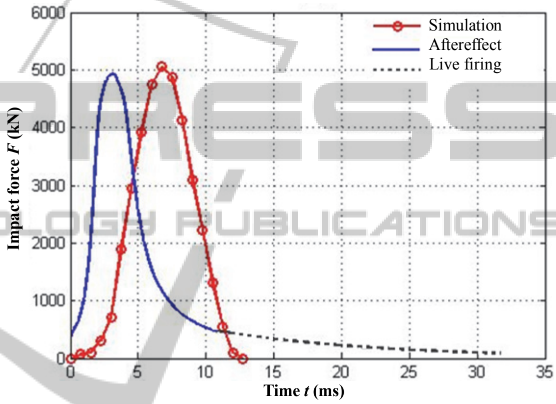

Figure 9: Contrast curve of a howitzer live firing with 2nd simulation firing.

Comparative data of three simulated impulses to howitzer live firing for three kind of major parameters are shown in Table 1.

Table 1: Comparative data of simulated impact to howitzer live firing on certain gun.

No.		Total impulse Ns	Impulse duration ms	Maximum impulse force kN
Live firing		27002	33.50	4813.5
Simulation	First	27794	15.60	4704.6
	Relative error %	2.94	-53.43	-2.26
	Second	27018	12.68	5048.8
	Relative error %	0.06	-62.15	4.89

5 CONCLUSIONS

In validation process for simulated impact of FIS, measured data of bore pressure resultant force of a howitzer 1 living firing is taken as truth value. Simulation effect of FIS can be established via comparisons of 2 simulated impact force values.

The following conclusions can be obtained from measured test data and calculated results in Table 1:

- Comparison results of selected three key parameters as impulse, duration of shock pulse and maximal impact force can be used as simulation credibility assessment basis of FIS;
- Maximum error of total impulse is 2.94 %, maximal value error of impact force is 4.89 %, which meet design requirements of 15% on simulation error;
- Maximum error for impulse duration is -62.15 %, which do not meet design requirement of 15% on simulation error;
- The shape of bore pressure resultant force curve in live firing is basically in accord with impact force curve of FIS.

Maximum error for two impulse durations all exceed 50 %, the main reason is that live firing data include 20ms after pill's getting out of gun bore, namely after-effect period. If after-effect period is subtracted, maximum error for impulse duration satisfies required simulation precision of 15%.

There are several advantages of the FIS over live fire testing. For example, FIS is easily operated indoors, not weather dependent. It also enables test engineers to examine any failure repeatedly during weapon approval test. FIS can be operated approximately two to three times per minute thereby enabling test engineers to examine the recoil systems' response to repeated rapid firing. However, the most important benefit of FIS is reduction in the cost associated with live fire testing of large caliber tank and howitzer cannons, which averages $500 to $2K per round.

REFERENCES

Aberdeen Test Center, 1994. *Report of Survey Conducted at U. S. ARMY COMBAT SYSTEMS TEST ACTIVITY*, Center of Excellence for Best Manufacturing Practices ABERDEEN, MD.

Aberdeen Test Center, 2010. *Firing Impulse Simulator* [online]. DoD TechMatch. Available from http://www. dodtechmatch.com/DOD/Lab/View Facility.aspx?id=71348. [Accessed on 7th February, 2015].

Cast, M., 2001. Army test move to 'virtual proving ground'. *National Defense*, (11), 62-64.

Di, C. C., Liu, L., Zheng, J., and Chen, Y. C., 2012a. Numerical simulation on dynamic recoil test with gun muzzle subjected to high-velocity impact. *Explosion and Shock Waves*, 32 (3), 323-327.

Di, C. C., Yang, Y. L., Qin, J. Q., and Cui, K. B., 2012b. Influences research of impact factors on gun recoil tester. *Chinese Journal of Gun Launch & Control*, (2), 25-28.

Faller, J. G., 1997. *Simulating firing loads provides flexibility and test repeatability* [online]. Available from http://www.thermotekusa.com. [Accessed on 7th February, 2015].

Gao, T., He, C., Fan, Z. J., and Guo, H. L., 2014. Analysis and evaluation of artillery fire simulation test. *Key Engineering Material*, (620), 632-637.

Lang, F. Y., and Li, W. J., 2012. Design of a Large Caliber Self-Propelled Gun Shooting Simulation device. *Chinese Journal of Gun Launch & Control*, (3), 52-54.

Liu, L., Di, C. C., Pan, B. Q., and Yao, J. J., 2011. Design and research on gun dynamic recoil simulation test mechanism. *Chinese Journal of Gun Launch & Control*, (1), 36-40.

Sanders, P., and Patenaude, A., 1996. *Study on the Effectiveness of Modeling and Simulation in the Weapon System Acquisition Process*, Final Report of Department of Defense of America, Washington D.C.

Yao, Y. W., 2001. Simulation test system of gun recoil and numerical calculations. *Acta Armamentarii*, 22(2), 152- 155.

Zhao, F. Q., Hua, L., and Yang, Z. J., 2003. Study on test and measurement for recoil mechanism of a tank gun. *Chinese Journal of Gun Launch & Control*, (s), 94-96.