Application of Digital Technology in Ballistic Mortar for Determining the Power of High Explosives

Tuan Son Nguyen

Center for Weapon Measurement and Expiration, Institute
of Weapon, Vietnam and School of Engineering, Griffith
University, Australia
Email: tuanson.nguyen@griffithuni.edu.au

Tien Thanh Nguyen

School of Information and Communication Technology
Griffith University, Australia
Email: tienthanh.nguyen2@griffithuni.edu.au

Thi Thu Thuy Nguyen

College of Economics
Hue University, Vietnam
Email: nguyenthithuthuy@hce.edu.vn

Anh Hai Nguyen

Vietnam Control & Instrumentation Services Company
Hanoi, Vietnam
Email: haip16@gmail.com

Abstract—The following paper researches into application of digital technology for explosives performance test, especially ballistic mortar test. The proposed approach provides a direct measurement of maximum throw angle of pendulum in ballistic mortar test. The measurement equipment for ballistic mortar (MEBM) is designed, produced, and applied in the defense industries in Vietnam. MEBM is developed and produced based on angle encoder, CPU S7 200, TD 200. With the new proposed approach, the measurement process, signal transfer, digital signal processing, data computing, and display are fully automatic. It overcomes the disadvantages of old approach, such as indirect measurement of throw angle, where measurement error depending on marker record, rule, and subjectivity of measurer. The testing and triggering detonator is integrated in MEBM.

Keywords—ballistic mortar test; explosives performance test; encoder; CPU S7 200

I. INTRODUCTION

The ballistic mortar has been used for long time in order to measure explosive power such as working ability and explosive strength as well as compare measurements of high explosion [1-4]. In defense industries, the applications of ballistic mortar play an important role in research activities, measurements, quality registration of explosives.

The ballistic mortar system consists of a massive steel mortar suspended in an aluminum structure. A heavy steel projectile is inserted in the mortar bore [1]. The explosive sample is detonated within a mortar cavity. With the explosion of sample that is tested, the projectile is fired out of the mortar. However, as a result of counteracting force, the mortar is swung from its balance position backwards. The maximum swing of the mortar is recorded. Taylor and Cook [2] proposed a slide-rule for direct reading of power for a preset ballistic mortar system. The disadvantage of this slide-rule is that it is not flexible. The more common approach, which is applied to measure the mortar movement, is to use marker records. From the maximum of marker records, the maximum throw angle of pendulum is calculated. The maximum throw angle is the most

important element that is used to calculate explosive strength as well as another important characteristics of explosive [1]. Therefore, the accuracy of result depends on the accuracy of marker records' measurement. In addition, arc is measured in millimeters and its range is around 300 mm, whereas the distance between the axis of the projectile and the center of rotation is about 5 m in length. Therefore, throw angle that is calculated indirectly from arc and length of pendulum in this case might not be accurate. Furthermore, measurement error of arc is depended on measurement of marker, rule, as well as the subjectivity of measurer. Finally, there are a few disadvantages in this approach. The results are not automatically calculated. The separate systems are used for testing and triggering detonator.

In order to tackle these issues, the following questions need to be addressed:

- How to measure directly the maximum throw angle?
- Can we calculate automatically the explosive strength as well as other characteristics?
- Can we design equipment that integrates both testing and triggering detonator functions?

II. LITERATURE REVIEW

A. Ballistic mortar

The mortar energy is obtained from the relation [1]

$$W_{obs} = MAg \left[1 + MAgT^2 / mr^2 \pi^2 \right] (1 - \cos \alpha) \quad (1)$$

where MA is the product of the mass of the pendulum and the distance between the center of gravity and the center of rotation, $g = 9.18 m/s^2$ (the acceleration due to gravity), T is the period of oscillation of the pendulum, m is the mass of the projectile, r is the distance between the axis of the projectile and the center of rotation, and α is the maximum throw angle. So, the mortar energy is calculated in kilo-joules (kJ). Fig. 1 shows a ballistic mortar that is used in Vietnam.

The strength of explosion is widely compared to the TNT equivalence (TNT_e), i.e., the effect from an equivalent mass of TNT [4]. It provides a importance but crude means of comparing the consequence of blast effect and likely hood damage distance relationship from a variety of explosion sources [4].

TNT explosive is used as a standard explosive and other samples that are needed for testing are compared to TNT explosive based on the following equation.

$$W_R = \frac{W_s}{W_{TNT}} \times 100 = \frac{1 - \cos \alpha_s}{1 - \cos \alpha_{TNT}} \times 100 \quad (2)$$

where W_R denotes TNT_e by ballistic mortar (%), W_s denotes the mortar energy of explosion sample, W_{TNT} denotes the mortar energy of TNT standard explosive, α_s denotes maximum throw angle of explosion sample, α_{TNT} denotes maximum throw angle of TNT standard explosive.

B. Angle encoder

Encoder has commonly used in a diversity of applications. Motor speed, tension control, linear measurement, multi-axis control, position measurement, conveying, spooling are a few practical examples of common encoder installations [5]. Different applications need different combinations of performance and functions to optimize their feature, such as some applications require repeatability, others accuracy, high resolution, or low-cyclic error for velocity loop control [5]. There is a range of angle encoders to select but none of them are capable of satisfying all requirements, therefore specific encoders are selected to meet the optimum balance of function [5]. Rotary encoders can be applied to measure distance, position, linear movement, rotary angles, speed, and velocity [6].

C. SIMATIC S7-200

SIMATIC S7-200 Micro PLC has applied in a wide variety of applications. It is fast, highly accurate, and capable of communication in real-time mode. It can be applied as a stand-alone Micro PLC solution or in connection with other control devices. The areas of application of the SIMATIC S7-200 include replacement of relays and contractor, more complex automation tasks in stand-alone mode, in networks, and within systems [7-9].

There are five different types of CPU in S7-200 family. CPU 221 is a compact CPU with simple automation tasks. CPU 222 is an expandable compact CPU for more complex tasks such as the ability to offer a compact package for more complex tasks and small system solutions. CPU 224 is designed for higher communication and computing requirements. It is a high performance CPU for complex tasks, which require special communication and speed capabilities. CPU 224 XP is a device for simple drive task. CPU 226 is a high performance CPU for larger technical tasks.

D. SIMATIC TD 200

The Text Display 200 (TD 200) is a text display and operator interface for S7-200 family. TD 200 includes four main features, such as display messages read from the S7-200 CPU, allowing adjustment of designated program variables, providing ability to force or un-force input or output points, and supporting ability to set the time and date for CPUs that have a real time clocks. Power for TD 200 can be supplied by CPU S7-200 through TD/CPU cable or separate supply.

III. METHODOLOGY DEVELOPMENT

In order to obtain the main objectives of this research, the main idea is that throw angle has to be directly measured instead of indirectly measured through arc. In addition, the explosive strength and other characteristics should be automatically calculated. The testing and triggering detonator and 'safety lock' in explosive testing should be involved in the new design. The 'safety lock' function is used to protect any accident that might trigger detonator. The testing and triggering detonator can be implemented only when 'safety lock' function is in 'OFF' mode. Otherwise, if that function is in 'ON' mode, the testing and triggering detonator cannot be implemented.

Applying digital technology in measurement, we propose a new approach to measure directly throw angle, to compute automatically, and to integrate testing and triggering detonator in the new equipment. Fig. 2 shows the module diagram of MEBM. The approach can be described as follows.

Sensor that is directly connected to the center of rotation is used to detect throw angle. The signal that is from sensor is sent to mainboard, and from there, the signal is connected to CPU. CPU is preprogrammed. When CPU receive signal, it will determine the maximum throw angle and compute automatically explosive strength. The results will be displayed on the display screen. The functions of power are that it supplies power for main board, sensor, as well as testing and triggering detonator.

A. Selecting Sensor

To be able to measure directly throw angle, we need to choose sensor that satisfy these requirements such as direct measure and high response time to measure this angle. As mention before, angle encoder is very good for measuring fluctuated angle, has high response time, and can measure directly the throw angle by directly connecting to center rotation. Encoder detects throw angle and converts throw angle into voltage pulses. In this case, when mortar is moved, the center rotation will be turned. Therefore, the center rotation of encoder that is connected with the center rotation of pendulum will be turned. As a result of the movement of encoder center rotation, the voltage pulses will be generated in two phase of encoder namely A and B.

In this study, we choose encoder that has high resolution and response time, which is encoder E50S8-8000-3-T-24. This encoder has 8000 pulse per 1 resolution and its response time is $0.5\mu s$. The maximum response frequency is up to 300 kHz. Another interesting feature of the chosen encoder is that with each pulse output of encoder is generated; one voltage pulse

output will be generated in phase A and B. The phase different of output between A and B is $\frac{T}{4} \pm \frac{T}{8}$, where T is 1 cycle of

phase A. Based on these characteristics and the ability of CPU, the event of 'start' pulse and 'end' pulse of both phase A and B is counted. By doing that, this approach will contribute to four times increase in the accuracy of throw angle measurement in comparison to the method that only count pulse from phase A or B. The throw angle can be determined by

$$\text{Throw angle} = \alpha = \frac{n \times 360^\circ}{8000 \times 4}, \quad (3)$$

where n denotes the number of 'start' and 'end' pulse of both phase A and B. Therefore, the measurement accuracy of this method can be up to $\frac{360^\circ}{8000 \times 4} = 0.01125^\circ$.

B. Selecting CPU in SIMATIC S7-200 family

There are some requirements that CPU has to have in this project.

- It has to be able to detect the start and end of voltage pulse.
- It is able to count these events.
- CPU is able to compute explosive strength and other parameters.
- It is able to connect with a display screen.
- It is able to take control of the whole process of explosive sample testing, such as testing and triggering detonator and 'safety lock' functions.

Consideration the above requirements, CPU 224 is selected in this research. It receives voltage pulse from encoder through main board. It is able to detect the turn direction of center rotation of encoder. In this project, CPU 224 can calculate the current throw angle, maximum throw angle. From maximum throw angle, the explosive strength and TNT_c are computed. The result is sent into the display screen. Furthermore, CPU 224 is used to generate signal in order to control the process of testing, triggering detonator, and 'safety lock' function.

C. Display screen

Display screen has to satisfy the following requirements.

- It is able to connect with CPU 224.
- It is able to display the results that are received from CPU 224.
- It provides human machine interface (HMI) feature.
- It allows interventions in the control program, for example setting point value changes or the setting of inputs and outputs.

To fulfill the above requirements, HMI TD 200 is selected. It can be connected with CPU 224 to display the results that are sent from CPU 224. The HMI feature of TD 200 allows us to

set input values as well as selecting the results that we need to observe.

D. Main board

The main board has to satisfy the following requirements.

- It is able to connect CPU 224 and voltage pulses from phase A and B of encoder.
- It has to have a testing and triggering detonator, and 'safety lock' feature.

The main board is designed by using Altium Designer software. This is a vital software for engineers to design a circuit diagram.

E. Program for CPU

The program for S7 200 is written by Statement List (STL) for S7-200 based on STEP7 program software package. The program is designed for implementing the following functions.

- Control the measurement process.
- Process voltage pulses signal from encoder.
- Determine the maximum throw angle.
- Compute parameters based on input signal.
- Configure the S7-200 CPU for TD 200 devices.

Fig. 3 shows mathematical algorithm to determine maximum throw angle. The mathematical algorithm program can be described as follows.

The program is set an interrupt that is triggered when anytime pendulum is turned its directions. When an interrupt event appeared the value in counter is saved. These values are always compared to each other to select the highest value. The highest value of counter is used to calculate the maximum throw angle.

IV. APPLICATION AND DISCUSSION

The MEBM is designed, produced, and applied in Institute of Propellants and Explosives and Institute of Weapon. Fig. 4 shows a picture of MEBM and Fig. 5 shows the inside of MEBM.

Thirty five different explosive samples were tested in order to compare between the new and old approach as well as to evaluate the MEBM. The results of explosive sample testing are showed in Table I-IV. These samples include 4 different types of explosive sample namely TNT, RDX, M1, and A4. In each Table, the maximum throw angle from the proposed approach and the arc from the marker record are reported. Based on arc from the marker record, the maximum throw angle the of old approach is calculated.

One of the objectives of this study is that with the same type of explosive sample the variability of results from the proposed approach has to be smaller than the old approach. In the statistic theory, the variability can be measured by the variance. Here to compare the variability of two approaches,

we compare variances of two approaches by testing the hypotheses:

$$\text{Null Hypothesis: } H_0 : \sigma_1^2 = \sigma_2^2$$

$$\text{Alternative Hypothesis: } H_1 : \sigma_1^2 > \sigma_2^2$$

where σ_1^2 , σ_2^2 denote the variance of the old approach and the proposed approach, respectively.

The hypotheses are tested by using F-Test Two Sample for Variance with 5% significance level on Microsoft Excel 2010. The testing results are presented in Table V-VIII. In these Tables, the mean, variance, observations, and degree of freedom are presented for each variable. According to the data from these Tables, the F value is higher than the F critical one-tail value in all cases. In addition, the P values are 0.001933, 0.036405, 0.001686, and 0.011686 for TNT, RDX, M1, and A4, respectively. All these values are smaller than significance level. Therefore, the Null Hypothesis H_0 is rejected, i.e., the variance of the old approach is higher than the proposed approach with 5% significance level. It demonstrates that the consistency in measurement of the proposed approach is higher than that of the old approach.

In addition, regarding the old approach, sometimes, the results are rejected because marker record does not work properly. Most of the time, marker record is not straight line and sometimes even has fluctuation. The accuracy of arc is affected as a result of these issues. With the new approach, rejection due to marker record not work properly is avoided. MEBL helps to improve the quality of the testing process, such as reliability, saving time, avoiding inaccuracy from measurer, marker record, and rule.

Other interesting thing is that, with the old approach, after projectile that includes explosive sample and detonator is inserted into the mortar, we need to wait until the mortar is self-balance before detonator can be triggered. However, it is impossible to check its balance due to the safety policy that mortar has to be separated. In a period of time that mortar is self-balanced, the marker record might be moved a little bit. Again, this might decrease the accuracy of old approach. With the new approach, MEBM allows the measurer to check the balance of mortar because currently throw angle is updated on the display screen. So, measurer can know exactly when the mortar is balance to trigger detonator. Why do we need to wait until mortar is balance? The reason is that if we trigger detonator when mortar is unbalanced, the result will be inaccurate. If the movement of mortar is backward, the explosive strength of sample is increased. Otherwise, it is decreased. In addition, in our approach, the mortar energy and TNT_e of explosive sample are automatically computed.

Finally, the testing and triggering detonator that are integrated with the main board and CPU as well as 'safety lock' feature improve the safety in the testing hazardous material process.

V. CONCLUSION

This research is concern with the application of digital technology to ballistic mortar in explosives performance test. With the new proposed approach, the measurement, signal

transfer, digital signal processing, data computing, and display are fully automatic. The MEBM illustrates its reliability in explosives performance test. MEBM provide a directly measurement method for ballistic mortar. It overcomes the disadvantages of old approach, such as indirectly measure throw angle, measurement error depending on marker record, rule, and subjectivity of measurer.

In future research, MEBM should be connected to a computer. By doing that, computer can be used to save automatically the test results and report of the measurement process. This approach can be applied in the measurement of any others throw angle of pendulum, especially in the measurement of counteracting force of B40, B41, SPG-9.

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Fig. 1. Ballistic mortar system in Vietnam

Fig. 2. Module diagram of MEBM

Fig. 3. Mathematical diagram operator to determine Max. throw angle

Fig. 4. Measurement equipment of ballistic mortar

Fig. 5. Inside MEBM

TABLE I. TESTING RESULTS OF TNT EXPLOSIVE

TNT			
No	Proposed Approach	Marker Record	
	α^0	Arc (mm)	α^0
1	2.819	293	2.907
2	2.74	288	2.857
3	2.725	299	2.966
4	2.775	299	2.966
5	2.8	297	2.947
6	2.775	280	2.778
7	2.712	290	2.877
8	2.775	295	2.927
9	2.712	260	2.579
10	2.787	296	2.937
11	2.662	288	2.857
12	2.7	290	2.877
13	2.7	295	2.927
14	2.775	300	2.976
14	2.775	300	2.976

TABLE II. TESTING RESULTS OF RDX EXPLOSIVE

RDX			
No	Proposed Approach	Marker Record	
	α^0	Arc (mm)	α^0
1	3.512	406	4.031
2	3.4	329	3.272
3	3.262	330	3.273
4	3.487	385	3.821

TABLE III. TESTING RESULTS OF M1 EXPLOSIVE

M1			
No	Proposed Approach	Marker Record	
	α^0	Arc (mm)	α^0
1	3.375	395	3.923
2	3.475	351	3.482
3	3.55	365	3.621
4	3.375	405	4.022
5	3.4	350	3.472
6	3.45	352	3.492
7	3.475	366	3.631
8	3.425	384	3.811

TABLE IV. TESTING RESULTS OF A4 EXPLOSIVE

No	A4		
	Proposed Approach	Marker Record	
	α^0	Arc (mm)	α^0
1	3.3	374	3.711
2	3.325	356	3.532
3	3.375	355	3.522
4	3.225	340	3.373
5	3.225	329	3.263
6	3.337	360	3.572
7	3.312	345	3.423
8	3.325	347	3.443

TABLE V. F-TEST TWO-SAMPLE FOR VARIANCES FOR TNT EXPLOSIVES EXPERIMENT

	TNT	
	Marker record	Proposed Approach
Mean	2.890267	2.7488
Variance	0.010472	0.002006
Observations	15	15
Degree of freedom	14	14
F	5.219183	
P(F $\leq$ f) one-tail	0.001933	
F Critical one-tail	2.483726	

TABLE VI. F-TEST TWO-SAMPLE FOR VARIANCES FOR RDX EXPLOSIVES EXPERIMENT

	RDX	
	Marker record	Proposed Approach
Mean	3.59925	3.41525
Variance	0.149704	0.012742
Observations	4	4
Degree of freedom	3	3
F	11.74865	
P(F $\leq$ f) one-tail	0.036405	
F Critical one-tail	9.276628	

TABLE VII. F-TEST TWO-SAMPLE FOR VARIANCES FOR M1 EXPLOSIVES EXPERIMENT

	M1	
	Marker record	Proposed Approach
Mean	3.68175	3.440625
Variance	0.045263	0.00356
Observations	8	8
Degree of freedom	7	7
F	12.71347	
P(F $\leq$ f) one-tail	0.001686	
F Critical one-tail	3.787044	

TABLE VIII. F-TEST TWO-SAMPLE FOR VARIANCES FOR A4 EXPLOSIVES EXPERIMENT

	A4	
	Marker record	Proposed Approach
Mean	3.479875	3.303
Variance	0.018493	0.002795
Observations	8	8
Degree of freedom	7	7
F	6.616011	
P(F $\leq$ f) one-tail	0.011686	
F Critical one-tail	3.787044	

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