Research and Analysis on firing accuracy of Naval Gun

Ziyu Liu1*, Weiyi Chen2

1School of Ordnance Engineering, Naval University of Engineering, Wuhan, Hubei, 430000, China
2School of Ordnance Engineering, Naval University of Engineering, Wuhan, Hubei, 430000, China
*Corresponding author’s e-mail: 5902415024@email.ncu.edu.cn

Abstract: This paper expounds the significance and function of studying the firing accuracy of naval gun weapon system, and briefly analyzes the firing error source, firing accuracy evaluation and firing error compensation method of naval gun. Through the establishment of the analysis model of firing accuracy, the principle of error sources affecting firing accuracy is clarified. Taking the projectile tracking method as an example, different firing correction methods of naval gun are analyzed, so as to improve the firing accuracy of naval gun.

1. Introduction
As an important part of shipborne weapon system, naval gun usually undertakes the important tasks of firepower killing and terminal defense. One of the main characteristics of modern war is long-range precision strike, so improving the firing accuracy of naval gun is the key problem to be solved in the process of long-range precision strike.

For artillery weapon systems, ‘accuracy’ mainly includes the following two meanings[1]:
1)The deviation between the impact point of each projectile relative to the average impact point, which is the dispersion error, and its size reflects the firing intensity.
2)By calculating the deviation between the actual firing data bound and the ideal firing data needed for the projectile to hit the advanced point, this is the firing data error, which reflects the firing data accuracy in the firing process.

The loading platform and use environment of naval gun are quite different from those of ground gun. On the one hand, because the surface ship is an unstable platform, the swing motion of the ship will have a significant impact on the firing of naval gun; on the other hand, due to the frequent changes of sea climate, the stress of the projectile will change, which will lead to the projectile deviate from the expected trajectory and reduce the firing accuracy. Therefore, firing accuracy has always been a hot issue in the research field of modern naval gun weapon system development. In recent years, a large number of relevant scientific and technological literature has been published. The research on firing accuracy of naval gun mainly includes firing error source, firing accuracy evaluation and firing error compensation method.

2. Firing error source
One of the important contents of the research on firing accuracy of naval gun is to make clear the cause and mechanism of firing error, so as to provide support for further defining the distribution characteristics of firing error. With the continuous development of sensor technology and the
continuous improvement of computer-aided analysis methods, many scholars have done a lot of research on the vibration characteristics of naval gun barrel in recent years by using different methods, and achieved certain results. Daniel realized the accurate simulation of muzzle flow field by using CFD model[2]; Mithilesh used the finite element method to analyze the deformation effect of gun barrel caused by projectile extrusion and the change of projectile assembly in bore[3]; Aiming at the problem of nonlinear vibration of gun barrel during firing, Mehmet established a variety of accurate finite element models to simulate the vibration characteristics of gun barrel under different firing conditions[4]. In addition to studying the characteristics of muzzle vibration, many scholars have also studied the source of firing error from other angles: John studied the uniform motion and maneuvering motion of air target, established the target maneuvering models in spherical coordinate system and Cartesian coordinate system, and analyzed the influence of target maneuvering behavior on the firing accuracy of naval gun[5]; Gast studied the influence of naval gun structure and projectile on muzzle vibration and firing accuracy through numerical calculation, and tests prove the correctness of numerical calculation[6]; David studied the influence of inertial measurement element precision index on miss distance, and deeply analyzed the influence mechanism between them[7].

In the domestic aspect, Bing Luo studied the influence of projectile initial velocity deviation on firing accuracy by means of theoretical calculation[8]; Zhaosheng Wang emphatically analyzed the causes of meteorological preparation errors, studied the characteristics of meteorological shooting errors caused by the inconsistency between meteorological observation time and firing time, and then studied the influence of spatio-temporal variation on firing accuracy[9]; Based on the construction of wave motion model and ship rocking model, Longjie Zhang established the error transfer model of naval gun firing against the air, and then studied the influence of ship rocking on the firing accuracy of naval gun[10]; On the basis of studying the dynamic change of weapon firing range under ship swing, Xutong Yu analyzed the relationship between target position and weapon firing range under the influence of ship swing by defining the maximum swing error angle, so as to study the influence of ship swing on the firing process[11].

In conclusion, the research results of the source of firing error of naval gun are mostly focused on the research of the ship gun barrel disturbance. However, with the improvement of equipment complexity and the progress of system theory, scholars in different fields focus more on the particularity of equipment, so the research on different types of shooting error sources has become a hot research object. At the same time, with the development of modeling and simulation software technology, more and more scholars have begun to focus on the establishment of appropriate simulation models to study the shooting accuracy under different conditions. Therefore, in the process of studying the firing error sources of naval gun, it is necessary to classify the error sources according to the operational characteristics of the equipment, as shown in Figure 1, and use the existing research results combined with the means of theoretical analysis to clarify the principle that the error sources affect the firing accuracy. On this basis, a suitable firing accuracy analysis model is established.
3. **Firing accuracy evaluation**

The evaluation of firing accuracy mainly covers two aspects: "Evaluation" means selecting the appropriate evaluation index to evaluate the accuracy of firing. "Estimate" means to predict the distribution characteristics of firing error.

In the aspect of firing accuracy evaluation, domestic scholars have studied the firing accuracy evaluation index of naval gun according to the characteristics of equipment and different requirements, and have obtained many results. According to the accuracy requirement of missile weapon shooting ground target, Gang Wang defined the circle probability deviation of hit area as the accuracy index of hit surface target, and studied the calculation method of circle probability deviation of hit area based on Monte Carlo integration method[16]; Based on the analysis of the traditional one-dimensional and two-dimensional probability error, Tianli Song puts forward the three-dimensional ball probability error as the evaluation index of missile weapon shooting accuracy. Combined with the requirements of accuracy evaluation, he uses Bayesian point estimation method and first-order approximation evaluation method to study the upper bound estimation and confidence zone estimation of ball probability error[17]; Ting Liu mainly analyzed the damage probability theory of weapon system, and combined with the vulnerability analysis conclusion of cruise missile, established the damage probability calculation model of weapon system for cruise missile firing[18]; Xiaobin Li analyzed the differences between hit probability and circle probability deviation in the field of shooting accuracy evaluation, and put forward the guidance probability ellipse deviation and guidance probability circle deviation as the accuracy index of missile weapon based on the characteristics of missile shooting[19].

With the rapid development of sensor technology and the wide application of radar system in the field of military science and technology, scholars all over the world have made some achievements in the field of firing error estimation. Kouichi observed the distribution characteristics of shooting error by using dynamic observer, and studied the gradual stability of the system error by using artificial neural network method[20]; Aiming at the problem of firing accuracy estimation of naval gun, Dimitri designed a continuous Petri net model with pertinence[21]; Shaoqiang Zhu analyzed the error transmission process in the process of naval gun dynamic design at sea, and studied the method of dynamic firing accuracy test at sea[22]. In addition, many scholars have also used statistical methods to study error estimation. According to the distribution characteristics of firing error of multi-functional artillery, Zhaojun Sha established a fuzzy clustering command and control model[23]; Yehong Du used the forward cloud generator of the cloud model to simulate the distribution characteristics of the
impact point on the shooting range[24].

In conclusion, in the evaluation of firing accuracy, the traditional linear probability error and circular probability error can be used as evaluation index to some extent to represent the shooting accuracy. However, with the change of operational requirements and the diversification of equipment types, it is more necessary and more valuable to select appropriate parameter indexes to evaluate the shooting accuracy combined with the requirements of combat tasks and equipment technology. At the same time, with the development of computer simulation technology and the wide application of statistical theory, the simulation model has a significant advantage in cost and efficiency to estimate the distribution characteristics of shooting errors of naval gun. In order to accurately and effectively estimate the distribution characteristics of shooting errors, it is necessary to establish a high reliability shooting accuracy analysis model and to use more accurate statistical theory.

4. Compensation method of firing error

The factors that affect the shooting accuracy of naval gun are various, so the compensation methods are not similar to the different factors. In view of the problem of shooting error compensation, scholars at home and abroad have put forward a good method from different angles and fields.

Starting from the calculation process of Shipboard Fire control system, Wernli designed a dynamic safety control system to optimize the coupling process between the effect module and the detection module in each subsystem, so as to realize the purpose of compensating the alignment error in the process[25]; Le analyzes and studies the mission characteristics and difficult problems of surface fire support, and establishes the simulation model of surface fire support based on discrete event simulation[26]; Baasch analyzes the process of projectile motion when the gun fires at the moving target, and designs a dynamic compensation model to compensate the aiming error in real time[27]. In the domestic aspect, Wei Wang combined with the conclusion of the analysis of the factors influencing the firing accuracy of the multiple launch rocket, and used the compound optimization algorithm to optimize the firing interval and firing sequence of the multiple launch rocket, so as to achieve the goal of improving the firing accuracy in the given firing environment[28]; Combined with the firing characteristics of self-propelled antiaircraft gun and the correlation of fire control calculation error, Kuiwu Li sets up a comprehensive compensation model of calculation error, and uses the error characteristics of the previous moment to compensate the solution process of the latter moment, thus realizing the task of improving firing accuracy[29].

In addition to the targeted compensation for the specific firing error, another effective way to improve the firing accuracy of naval gun is firing correction. In view of this aspect, scholars have also carried out a lot of valuable research. Mostafa studied the calculation method of correction angle and proposed a correction method based on discrete-time transfer matrix[30]; Yuansheng Li studied the shore-to-shore calibration process of naval gun weapons, analyzed the principles of correction distance of one-dimensional trajectory correction projectile and trajectory fitting virtual calibration, and established the corresponding model[31]; Weiyi Chen improved the naval gun calibration method based on the projectile tracking method by using the NAGA-II algorithm, thus achieving the goal of improving the firing accuracy of the naval gun, the principle is shown in Figure 2[32]. In the figure, $T_0$ is the target position before shooting, $H_0$ is the shooting advance point, then $H_0H_1$ reflects the estimation deviation of shooting advance point caused by the inaccurate assumption of target motion state, and $QH_0$ reflects the error of shooting data.
In addition, many scholars also focus on using new technical means to obtain more real data, so as to improve the accuracy of calibration, such as using photoelectric systems to measure the deviation of projectiles and targets\cite{33}, real-time monitoring of aerodynamic parameters of projectile\cite{34}, using ultra long range radar combined with information ammunition to improve range\cite{35} and so on.

To sum up, when we study the error compensation technology of naval gun firing accuracy, we can consider it from two aspects: one is to start with firing correction technology, we can study and explore new firing correction methods on the basis of existing firing correction methods, so as to realize the goal of reasonably using the obtained parameters to compensate firing data. At the same time, new technologies in other fields can be applied properly in the process of calibration to obtain more accurate and reliable parameters, so as to achieve the task of improving the accuracy of calibration. On the other hand, based on the results of firing accuracy analysis, under the premise that the specific error source has a significant impact on the firing accuracy, we should study and explore reasonable means to compensate the error, so as to improve the firing accuracy.

5. Conclusions
As a complex system, the firing accuracy of naval gun weapon system is affected by many complex factors, which has gradually become a very promising research field and attracted a large number of scholars' extensive interest and in-depth research. But so far, there are still many key technical problems to be solved. In order to understand the advantages and disadvantages of the existing research results at this stage, and make clear the future research direction, this paper reviews the research results of domestic and foreign scholars on the firing accuracy of naval gun in recent years from three aspects of firing error sources, firing accuracy evaluation and firing error compensation methods, and classifies and summarizes the related research scientifically.

According to the research on the source of firing error, combined with the previous research results, it can be concluded that firing error is mainly composed of projectile dispersion error and firing data error. The dispersion error of projectiles is mainly caused by the comprehensive influence of factors such as barrel vibration, environmental weather change and ballistic condition disturbance. The firing data error is mainly formed by the accumulation and superposition of the system errors in each subsystem of the naval gun weapon system in the process of tracking, prediction, settlement and aiming.

Aiming at the research of firing accuracy evaluation, it is very necessary to select the appropriate parameter index according to the requirements of combat mission and the technical characteristics of equipment. At the same time, the establishment of high reliability analysis model of shooting accuracy and the use of more accurate statistical theory can more accurately and effectively evaluate the shooting accuracy.

Aiming at the research on the compensation method of firing error, on the one hand, on the basis of the existing calibration methods, the new technologies in other fields can be reasonably used to obtain more accurate and reliable parameters, so as to improve the accuracy of calibration. On the other hand, on the premise of defining the specific error source, we can explore and study reasonable means to
compensate the error, so as to achieve the purpose of improving the firing accuracy.

This paper summarizes the research methods of firing accuracy of naval gun from the perspective of system. However, for the accuracy of the whole naval gun weapon system and its subsystems, there are still many problems to be further studied:

- More accurate and efficient fire control solution model.
- More reliable analysis model of firing accuracy.
- More effective method of firing error compensation.

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