Motion analysis of a artillery’s opening mechanism based on Virtual Prototyping Technology

WANGBing-zhe1,a, LIWei1, WUXing-chao1 and ZHAOWei2

1The 713th Research Institute of China Shipbuilding Industry Corporation, Zhengzhou Henan 450015, China
2Nanyang Hongyuan Mechanical & Electrical Technology Co.,Ltd, Nanyang Henan 473082, China
a WANGBing-zhe: wangbingzheart@163.com

Abstract. The bolt-operating mechanism is the principle part of the launching system, and it is the main mechanism demonstrated in the design and research of the launching system. Compared with the traditional bolt-operating mechanism, the new bolt-operating mechanism is greatly improved on principle design and structure innovation. The method of dynamic analysis of multi-rigid-body cannot specifically analyze the structural strength of components on specific positions. Therefore, the rigid and flexible coupling method is used in the motion analysis of the bolt-operating mechanism. This paper establishes the rigid and flexible coupling model of the mechanism based on software ANSYS and ADAMS, verifying the rationality of the mechanism by comparing the curve of the breech-displacement and the stress curve of U3 test points in the simulation and experiment, and gives useful suggestions on the optimization design of the bolt-operating CAM.

1. Introduction

The bolt-operating mechanism is a complex multi-rigid mechanism involving various constraints and a large number of spring forces and collision problems. As a key mechanism in the launching system, whether the mechanism operates smoothly or not has a decisive influence on the achievement of the whole gun performance index. Therefore, the research on the bolt-operating mechanism has always been the focus of relevant researchers.

In order to carry out the design and research work of the bolt-operating mechanism more effectively, the relevant practitioners have done a lot of research and analysis work on the mechanism using different methods. Literature 1 and 2 studied the whole-system combat application of airborne weapon systems[1,2]. Literature 3 quantitatively analyzed the failure cause of the bottom edge fracture of the cartridge during the shelling process by means of theoretical calculations[3]. The influence of the opening distance on the bolt-operating mechanism was studied in Literature 4[4], and Literature 5 and 6 established the multi-rigid dynamics model of the bolt-operating mechanism, respectively analyzing the mechanism rationality of the virtual prototype and the influence of the shelling resistance on the opening resistance[5,6]. Literature 7 analyzed the dynamic characteristics of an external-energy automatic weapon for different radio frequency[7], while in the literature 8, the mechanical effects of the bolt-operating direction on the structure were studied by inputting the force obtained by the ADAMS multi-rigid analysis into the ABAQUS to analyze the sub-components[8]. For a long time, the research on the bolt-operating mechanism mainly focused on the rationality and theoretical research of
the mechanism, while there were few analyses of the mechanism from the perspective of critical component failure.

In this paper, the rigid-flexible coupling method is applied to the dynamics research of the bolt-operating mechanism, and the virtual prototype model is established by software ANSYS and ADAMS. The stress and strain of key components are emphatically analyzed in order to verify the rationality of the mechanism and propose feasible suggestions for the later prototype improvement.

2. Operating principle
The bolt-operating mechanism mainly includes gun breech, bolt, cartridge extractor, crank arm, crank arm shaft, bolt-operating cam and bolt-operating template mounted on the cradle, with the characteristics of simple structure and reliable shelling.

As shown in Figure 1, The bolt-operating cam and the bolt-operating template react when the recoil portion is re-entered. The rotation of the bolt-operating cam drives the rotation of the crank arm mounted on the crank arm shaft, and the roller mounted on one end of the bolt-operating lever presses the compression spring of bolt-closing spring tube to store energy. At the same time, the cartridge extractor is pressed by the bolt body and the tail end of the shaft. The cartridge extractor axis slides in the shaft chamber on the gun breech and the bolt, completing the shelling action. When the bolt is in place, the plane on the inner side of the cartridge extractor and the plane on the side of the bolt body are combined to keep the bolt in the opening state.

![Figure 1. Model of bolt-operating mechanism.](image)

3. Virtual prototypes of ANSYS and ADAMS

3.1 Establishment of model
Based on the software Creo, this paper establishes a three-dimensional model of the artillery’s launching system, and then imports the established three-dimensional model into ADAMS. Due to the complex structure of the launching system, the entities and their interrelationships are difficult to process in the simulation, and many factors have little effect on the simulation results. Therefore, the model needs to be processed twice according to the purpose and specific content of the simulation.

The modified model is imported into ADAMS in Parasolid format. The model has 11 parts, which are a gun breech, a bolt, a cartridge, a cartridge extractor, a push rod, an axis of rotation, a bolt-operating template, a bolt-operating cam, a roller, a small roller, and a support tube. The parts list is shown in Figure 2.
3.2 Establishment of a sports pair and collision contact

The simulation model uses line constraints instead of contacts as much as possible. This can improve the body contact accuracy, reduce the amount of calculation, and improve the simulation success rate. Under the premise of ensuring the simulation effect, the contacts are replaced with as many line constraints as possible. After the constraints are replaced, the model has 10 rigid bodies, 1 fixed pair, 2 moving pairs, 3 rotating pairs, and 1 drive. The total degree of freedom of the model is: $10 \times 6 - 1 \times 6 - 2 \times 5 - 3 \times 5 - 1 = 28$.

In addition to the above six constraints, the action of the counterrecoil process is more realized by collision to transfer energy.

In the collision contact, unless it is a very complicated contact shape, if the condition allows, line contact should be used whenever possible.

In this paper, the impact function method is adopted for collision contact, where the contact stiffness coefficient is calculated by Hertz theory:

$$K = \frac{4[R_iR_j/(R_i+R_j)]^{1/2} [3\pi (h_1+h_2)]}{\pi (h_1+h_2)} \quad (1)$$

$$H_i = (1-v_i^2)/(\pi E_i), i=1,2 \quad (2)$$

Where:
- $R_i$ - the radius of the i-th member contact surface;
- $v_i$ - the elastic constant of the i-th component;
- $E_i$ - the modulus of elasticity of the i-th member.

The topological relationship between the gun breech and each component is shown in Figure 3.
3.3 Establishment of a flexible body

During the actual motion, the bolt-operating cam is very flexible with respect to the mechanism such as the gun breech, and its deformation will affect the dynamic response of the components and its own stress and strain, and then influence the rationality judgment of the mechanism.

This paper relies on the finite element analysis software ANSYS and uses two cell formats of Brick 8 node 185 and 3D mass 21, to mesh the entities and connected nodes respectively. Moreover, a rigid region is established by connecting the node units and the node on the rigid-flexible contact surface, to connect other rigid bodies, finally generating a finite element model as shown in Figure 4.

Considering that the contact between the rigid body and the flexible body involves a lot of non-linear calculations, the contact involved in the corresponding rigid body should first be deleted before the flexible model in the ADAMS replaces the rigid body. Then, the modal neutral file generated in ANSYS is imported into ADAMS, replacing the corresponding rigid body, and the flexible body of the bolt-operating cam is generated, shown as Figure 5. The KSTL_KSMB is added by the rigid-flex contact module in the contact, so that the rigid-flexible coupling model of the entire bolt-operating mechanism is created.
3.4 Applied load

The launching system is subjected to lots of load during the bolt-operating process. For the purpose to control the variables in the simulation process, the counterrecoil force and the shelling resistance measured in the test, and the spring force of the push rod spring and the spring force of the bolt-closing spring obtained in the design process serve as known conditions on the corresponding components of the mechanism.

3.4.1 Applied counterrecoil force

The counterrecoil process of the launching system is an inseparable whole, where the process is divided into two phases based on the motion direction of the gun breech. The first stage: the gunpowder force acts on the bottom of the cartridge to generate the recoil, and the counterrecoil machine stores energy during the recoil of the gun breech; The second stage: After recoiling in place, the counterrecoil machine releases energy, compelling the gun breech to perform the counterrecoil action until the counterrecoil is in place. The bolt-operating process takes place in the latter stage, so here is mainly studied the second stage.

The counterrecoil force in the research process is the combined force of the acting force of the counterrecoil machine on the gun breech and the force of various friction. In order to reduce the influence of the unrelated factors on the simulation results, the counterrecoil force measured by the test is directly used in this paper. The data obtained in the test is imported into the software ADAMS, obtaining the counterrecoil force curve as shown in Figure 6, and called in the counterrecoil force acting on the gun breech.

3.4.2 Applied shelling resistance

The shelling resistance refers to the resistance suffered by the cartridge extractor pulled out from the inner bore. Its cause is mainly because the gunpowder force on the cartridge causes the deformation of the wall, and then the friction between the cartridge and the inner bore is generated. The friction coefficient of the cartridge and the inner bore, the length of the cartridge, the deformation of the cartridge, and the diameter of the cartridge are all factors influencing the shelling resistance. Here, the shelling resistance is approximately calculated by an empirical formula:

\[ F = f_0 N \pi (l_k - l_x)/l_k \]  

(3)

Where:

- \( f_0 \) - the coefficient of static friction;
- \( N \) - the extrusion force from the cartridge residual deformation;
- \( l_k \) - the length of the cartridge;
the length of the cartridge extracted out \[^7\].

In ADAMS, the shelling resistance is applied to the bottom of the cartridge in the form of a one-way force and the STEP statement \[\text{STEP} (DX, 0, F_l, l_k, 0)\] in the function is called.

4. Test verification and analysis
The simulation calculation of the bolt-operating mechanism under typical shooting conditions is carried out, with the counterrecoil force measured in a single shot test and the shelling resistance obtained by the approximate formula as known inputs, and various simulation data in this state are obtained. In this paper, the rationality verification of the virtual prototype is carried out by comparing the simulation results with the experimental data, and suggestions for improvement are given in the aspects which the test is difficult to measure.

According to the previous research results of the parts of the bolt-operating mechanism\[^9\], in the test, the strain gauges and displacement sensors were installed on the corresponding measuring points on the bolt-operating mechanism and the gun breech, and the data processing system was used to process and output the data. The main test equipment is shown in Table 1.

### Table 1. List of main test equipment.

| Equipment                  | Type                        |
|----------------------------|-----------------------------|
| Date Collection System     | DEWE-50-PCI-32              |
| Displacement Sensor        | SX50-1000-10V-KA            |
| Displacement Sensor        | KFG-2-120-D17-11L1M2S       |
| Power Supply               | SS2325                      |

4.1 Test verification

4.1.1 Verification of counterrecoil displacement test

Figure 7 shows the functional block diagram of displacement measurement. Under the condition that the gunpowder dose is fixed, the data collected by the system is stable and can be used to check the rationality of the simulation data. The counterrecoil displacement curve of the test acquisition is shown in Figure 8.
Figure 8 displays the displacement curve of the gun breech counterrecoil of the bolt-operating mechanism in the typical shooting state. Because the mechanism is subjected to various external loads such as collision contact force and counterrecoil force during its motion, the motion process is a comprehensive result of multiple forces. Comparing the simulation data and the experimental data in Figure 8, it can be found that the virtual prototype can complete the counterrecoil process of the gun breech at 0.36s, which is basically consistent with the data collected in the experiment at 0.34s, and the curve trends are the same.

4.1.2 Test verification for the test point of bolt-operating cam
According to the results of ABAQUS analysis in earlier stage\textsuperscript{[8]}, a dangerous point can be found in the inner arc segment of the bolt-operating cam, and the maximum dangerous stress exceeds the yield limit of the material. Therefore, the stress checkpoint is set at the inner arc segment of the bolt-operating cam, and the position of the test point U3 is as shown in Figure 9.

The test device mainly includes a strain gage and a data acquisition system, and then the collected strain data is converted into stress data by a formula calculation. The functional block diagram of the strain measurement is shown in Figure 10.

For this test point, the flexible body of the virtual prototype corresponding to the unit ID is 65. After the simulation study, the data processing for the flexible body stress is performed to obtain the maximum stress value of the corresponding node, as shown in Figure 11.
Figure 11. The date of VON MISES Hot Spots.

Figure 12 presents the stress variation curve of the test point U3 in the test. It can be obtained that the test point experienced four times stress changes, with the maximum stress of 651.938MPa, which has a maximum stress value error less than 3% at 669.061MPa corresponding to the grid unit No. 65 in Figure 11.

From the comparison of the above two tests, it can be obtained that the simulation experiment data are basically consistent with the test data, with roughly the same curve trend, and the virtual prototype mechanism is reasonable. The model data can provide feasible suggestions for the model improvement and optimization.

4.2 Analysis of the dangerous point of bolt-operating cam

The earlier stage of ABAQUS analysis applied the contact force obtained in the ADAMS analysis to the finite element model as an external load. Because the maximum stress on the bolt-operating cam under the external load exceeds the fatigue strength of the material, resulting in the damage of the dangerous point of the bolt-operating cam, and obtaining the conclusion that the damage point is the dangerous point of the bolt-operating cam[8]. In this paper, from the stress nephogram of the bolt-operating cam obtained by rigid-flexible coupling, it can be found that the stress concentration during the collision between the bolt-operating cam and the bolt-operating template occurs first in the vicinity of the test point U3, and then passes to the vicinity of No. 264 mesh unit, forming the final stress concentration. The stress nephogram when the simulation results in the maximum stress is shown in Figure 13.
Figure 13. The stress nephogram of the bolt-operating CAM.

Combined with the simulation data of each node in Figure 11, the maximum stress value of the dangerous point of the bolt-operating cam (No. 264 grid unit) is 1406.43MPa, which exceeds the material yield strength by 7.5%. A test point is recommended to add to the position corresponding to No. 264 grid unit of the bolt-operating mechanism in the next stage test.

5. Conclusions
Based on the software ANSYS and ADAMS, the rigid-flexible coupling model of a bolt-operating mechanism is established. The simulation analysis of the mechanism is carried out according to the working principle of the launching system. The comparison of the recoil displacement curve and the stress curve of the test point U3 under typical shooting conditions, verifies the structural rationality of the artillery’s bolt-operating mechanism. It is suggested that a test points be added to the dangerous position obtained in the analysis in the latter tests to detect the reliability of the mechanism. The test results of the simulation comparison show that it is feasible to analyze the bolt-operating mechanism mode by virtual prototyping technology, which can observe the data that is not easy to measure, provide data support for structural optimization, and provide a new analytical method for simulation research of similar structures.

References
[1] Yu Chi, Li Jianren, Zhang Gangfeng, Wu Peijun. Airborne weapon launching system simulation test [J]. Sichuan Ordnance Journal, 2015, 36(08):149-152
[2] Tang Jixin. Airborne weapon launching technology and its research [J]. Aeronautical Science and Technology, 2016, 27(04):1-8.
[3] Fu Jianping, Song Mingming, Lv Shile, Mao Zhijun. The gun tube failure mechanism [J]. Journal of Ordnance Engineering College, 2013, 25(04):20-23.
[4] Yang Yanfeng, Zheng Jian, Di Changchun, Chen Jingwen. Design and dynamic simulation analysis of the experimental device of gun bolt system [J]. Machinery Design & Manufacture, 2015, 11:247-249+252.
[5] Shao Xinjie, He Zhongbo, Liu Jinhua, Tian Guang, Cao Lijun. Simulation of the kinematics and dynamics of the bolt based on virtual prototype [J]. Fire Control & Command Control, 2014, 39(07):14-17.
[6] Fu Shuai, Gu Keqiu, Zhang Junfei. Dynamic analysis of the recoil bar resistance of a large caliber gun [J]. Journal of Gun Launch and Control, 2013, 04:19-23+29.
[7] Wang Jingya, Zhou Kedong, He Lei, Liu Yin. Study on Virtual Prototype Technology of an External Energy Automatic Weapon [J]. Computer Simulation, 2013, 30(10):27-31.
[8] Liao Hui. Research on mechanical problems when the direction of artillery unlatch changes [D]. North University of China, 2015.
[9] Zhang Wenyan. Motion Simulation Analysis of Extended Range Mechanism Based on Pro/E and ADAMS [J]. Coal Mine Machinery, 2015, 36(02):267-270.
[10] Zeng Yonghui, Wang Hongliang, Liu Jun. Simulation of dynamic characteristics of a missile launching system [J]. Tactical Missile Technology, 2013, 01:32-37+41.