Model updating of gun recoil mechanism based on time domain response

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Abstract. For gun launching dynamics modeling, the accuracy of the recoil and counterrecoil model is important. In order to improve the accuracy of gun recoil mechanism modeling, the rigid-flexible coupling firing dynamics model of a small-caliber gun was established, and the recoil displacement of the gun was tested by live firing test. Aiming at the error between the simulation curve and the test curve of the recoil displacement changing with time, taking the correlation coefficient of the two curves as the objective function, the dynamics model of the recoil mechanism was modified based on the time-domain response using the optimization algorithm. The modified results show that the difference of the maximum recoil displacement decreases from 9% to 0.1%, and the similarity between the simulation curve and the test curve reaches 0.99. The modified results based on the time-domain response effectively improve the accuracy of the recoil model, so that the established dynamics model can more truly reflect the dynamic characteristics of the recoil mechanisms, and provide the basic conditions for ensuring the simulation accuracy of the launch dynamics model.

1. Introduction
The recoil mechanism is called the heart of the gun. The gun body is elastically connected to the gun mount by the recoil mechanism. The breech pressure acting on the gun body is buffered by the recoil and counterrecoil mechanisms, so that the force acting on the gun mount is changed to the recoil resistance of the recoil mechanism [1]. During firing, on the one hand, the stability of the gun is directly determined by the recoil resistance; on the other hand, the arrangement and the load of the recoil mechanism are closely related to the muzzle vibration, which is one of the key factors affecting the accuracy of gun firing [2]. Therefore, for the gun launch dynamics simulation, the accuracy of the recoil resistance directly determines the credibility of modeling and simulation.

During the design process of the recoil mechanism, it’s assumed that the liquid is incompressible and the liquid flow is a one-dimensional steady flow. However, the liquid parameters of the recoil mechanism are practically affected by the temperature, the cavitation, and the compressibility during firing. Therefore, there is a certain degree of error between the design value and the actual value for the liquid parameters of the recoil mechanism during firing [3]. Generally, during the gun launch dynamics simulation, the design value of the recoil mechanism parameters is directly used, which leads to deviation of the simulation results to the test results. In addition, the change of recoil resistance with time has an important effect on the gun vibration. Therefore, it is necessary to perform the recoil mechanism parameter correction based on the time domain response.

The time-domain response-based model correction technology uses the time-domain response of the model and the test structure. Compared with the frequency-based and modal-based correction
methods, the time-domain signals carry more information and can reflect the dynamic response of the test structure more truly and effectively. Moreover, the time-domain response signal can avoid frequency truncation, and can cause little error due to re-analysis of the data, which makes the model updating accuracy highly [4]. The comparison method of time-domain signals has been studied, and the methods of residual errors between time-domain signals have been analyzed, which provided a theoretical basis for model modification based on time-domain responses [5]. The residuals of feature quantities were defined by using the experiment and finite element simulation signals to obtain the mathematical expressions, and multiple optimization algorithms were used to obtain the optimal solution [6]. For the updating of the rigid-flexible coupled launch dynamics model of the infantry fighting vehicles, the similarity between the simulated and measured data was used as the objective function, and the support vector machine response surface method was used [7]. Up to now, the research on the parameters of the gun recoil mechanism is mainly focused on the optimization design of recoil mechanism, while the research on the model updating of recoil mechanism parameters is little [8-10].

In this paper, the rigid-flexible coupling firing dynamics model of a small-caliber gun has been established. The parameters of the recoil mechanism were studied based on the time-domain response correction method and the genetic algorithm. It has been shown that the time-domain response correction method effectively improved the accuracy of the recoil mechanism model and provided the basis for the muzzle vibration simulation.

2. The gun rigid-flexible multibody dynamics model

2.1. Basic assumptions

The basic assumptions for establishing the rigid-flexible coupling firing dynamics model of the small-caliber gun are as follows.
- The inertia of the spring is ignored.
- The gun barrel is assumed to be an elastic body, and other components are rigid bodies.
- The gun recoil mechanism connects the recoil part and the cradle. The recoil part moves back and forth relative to the cradle.

2.2. Barrel Finite Element Model

Figure 1 shows the finite element meshes and constraints of the barrel. Figure 2 shows the calculated first six order bending mode shapes of the flexible barrel. By calculation, the frequencies of the first six bending modes are: 71Hz, 71Hz, 437Hz, 437Hz, 1136Hz, and 1136Hz. Due to the axisymmetric characteristic of the barrel, each frequency in the first six modes of the barrel corresponds to two mode shapes, and the bending directions of the two mode shapes are perpendicular to each other.

![Figure 1. The finite element meshes and constraints of barrel.](image-url)
2.3. Rigid-flexible coupling launch dynamics model

A rigid-flexible coupling launch dynamics model including turret, cradle, gun box, barrel and recoil mechanism was established [11]. The topological graph of the connection relationship of the components of the gun is shown in figure 2, where H1 is a fixed pair, H2 is a rotating pair, H3 is a contact pair, H4 is a contact pair, and H5 is a contact pair. The rigid-flexible coupling model has 1 flexible body and 9 rigid bodies as shown in figure 3.
2.4. Differential equation of recoil motion
The differential equation of the gun recoil motion is:

\[ m \ddot{y} + k_b y = S p - k_b y_0 - F_f - u \dot{y}^2 - m g \sin \alpha - F_p \]  

(1)

where, \( m \) is the mass of the recoil part of the gun, \( y \) is the recoil displacement, \( y_0 \) is the preload of the bumper spring, \( k_b \) is the stiffness of the bumper spring, \( p \) is the bottom pressure, \( S \) is the cross section area, \( F_f \) is the friction of the guide rail between the recoil part and the cradle, \( u \) is the hydraulic damping coefficient, \( \alpha \) is the shooting angle, \( F_p \) is the forward force generated by the powder gas ejecting through the muzzle brake. After solving the equation (1), the recoil resistance \( R \) can be calculated as follows,

\[ R = k_b (y + y_0) + F_f + u \dot{y}^2 \]  

(2)

The recoil displacement result of one shot with a 0-degree shooting angle calculated according to the design values is shown in figure 5.
3. Recoil Displacement Measurement

By pasting the markers on the gun barrel and the cradle respectively, and by using the high-speed camera measurement system, through optical calibration and image processing, the relative positions of the two markers in each frame were extracted. The layout of the high-speed camera and the markers is shown in figure 6.

The high-speed camera measurement system captures the movement of the marker and performs digital image processing to obtain the marker displacement. The measurement system mainly includes high-resolution high-speed cameras and installation devices such as brackets, heads, and tripods. In order to meet the requirements for high-precision measurement of marker displacement, the camera should have sufficiently high resolution and frame rate. The high-speed camera used in this test has a resolution of 1280 × 800 pixels. The shooting frame rate at full resolution can reach 16000fps. Then, the grayscale processing was performed on the captured image, and then other related processes such as smoothing, sharpening, enhancing, filtering, and denoising are performed, and the grayscale images were converted to binarized images in order to reduce the amount of the data processing. Finally, the measured curve of the recoil displacement changing with time is shown in figure 7.
By comparing with the test curve, as shown in figure 8, there was about 9\% difference in the maximum value of the recoil displacement for the simulation curve. It is to say, there is a large error between the measurement result and the simulation result of the rigid-flexible coupling launch dynamics model by using the design value of the recoil mechanism parameters.

4. Model updating

4.1. Objective function

The correlation coefficient was utilized to characterize the similarity between the test curve and the simulation curve of the recoil displacement changing with time. The correlation coefficient between the two time-domain signals can be expressed as:

$$\rho(a, b) = \frac{\sum_{i=1}^{N}(a_i - \bar{a})(b_i - \bar{b})}{\sqrt{\sum_{i=1}^{N}(a_i - \bar{a})^2}(b_i - \bar{b})^2}$$  \hspace{1cm} (3)\)  

where, \(a\) and \(b\) represent test values and simulation values, \(a_i\), \(b_i\) represents the test value and simulation value corresponding to the \(i\)th time point. The correlation coefficient value ranges from -1 to +1, and +1 means that the two time-domain signals are exactly the same, and -1 means that the two
time-domain signals are completely opposite. Therefore, the objective function to determine the model correction is:

$$\max: s = \rho(a, b) \quad (4)$$

4.2. Design variables

According to the design principle of the recoil mechanism and the nonlinear differential motion equation of the recoil mechanism, it can be concluded that the parameters of the dynamics model of the recoil mechanism are: recoil hydraulic resistance coefficient $u_1$, the counter recoil hydraulic resistance coefficient $u_2$, spring stiffness $k_b$, and friction coefficient $\mu$ of the guide rail between the recoil part and the cradle.

4.3. Optimization Algorithm

Because the model updating can actually be changed to optimization of the objective function, the choice of the optimization algorithm is very important. The rigid-flexible coupled dynamics model of this example has nonlinear factors such as friction and contact, which is highly nonlinear. It makes traditional optimization search methods such as gradient method and Newton iteration method difficult to get the global optimal solution. So the genetic algorithm which has great advantages for the global optimization was used as the optimization algorithm for the model updating.

Genetic algorithm is a global probability search algorithm based on biological mechanisms such as natural selection and genetic mutation [12]. For the genetic algorithm, the chromosomes represented by one-dimensional string structure data correspond to data or arrays. Each position of the string corresponds to the gene, and the value at each position corresponds to the value of the gene. The string composed of genes is the chromosome. A certain number of individuals make up a group, and the degree of adaptation of each individual to the environment is called fitness.

The relevant parameters and selection of the genetic algorithm in the application process are as follows:

- **Population size.** The population size indicates the number of individuals in each generation of the population. If the size of the population is large, the efficiency of the calculation is low. Oppositely, if the size of the population is too small, the efficiency of the calculation will increase. However, the diversity of the population will also be greatly reduced, which can increase the possibility of premature genetic calculation. In this calculation model, the population size is selected to be 20.

- **Selection probability.** The selection probability determines the number of copies of the individual parents to the offspring. If the selection probability value is too large, it will easily lead to duplication of groups, which is not conducive to the evolution of individuals. In some genetic calculations, the selection probability is zero, that is, the progeny population is composed of individuals produced by crossover or mutation. In order to save the optimal individual, the selection probability selected during the genetic calculation is 0.1.

- **Crossover probability.** It is the proportion of chromosomes participating in the crossover operation to the total number of chromosomes. Crossover is the main method of generating new individuals in genetic algorithms, so the value is generally large. However, if the value is too large, it is easy to destroy the excellent genes contained in the existing individuals. If the value is too small, the generation rate of new individuals will be very slow. The value range is generally selected between 0.4 and 0.99.

- **Probability of mutation.** Probability of mutation refers to the proportion of the number of mutated genes in the total number of chromosomal genes. Too large value can easily lead to the loss of outstanding individual genes, and makes genetic algorithms deviate from directed search similarly to random search. Generally, The value ranges from 0.0001 to 0.1.

- **Maximum iteration algebra.** The maximum iteration algebra determines the end of genetic calculation. Its selection is closely related to the content of the actual genetic calculations. If some evolutions are slow, the genetic algebra must be larger, or the genetic calculations have not yet
reached stability and will be terminated, which is not in line with the original intention of genetic calculations. For the fast evolution process, the genetic algebra should be small. Otherwise it is a waste of computing time, and genetic computing may not continue to evolve.

The basic genetic algorithm generates a new generation of population by copying, transforming and mutating the biological genes of a certain generation of population, and then repeats this process until the performance of the population or the most advantageous reaches a satisfactory level. The genetic algorithm process is shown in figure 9.

![Flow chart of genetic algorithm.](image)

4.4. **Optimization results**

The genetic algorithm was used to update the parameters of the recoil mechanism model based on the test time-domain curve of the recoil displacement. The simulated recoil displacement curve and the measurement curve are shown in figure 10, the correlation coefficient reaches 0.99, and the maximum value of the recoil displacement differs by 0.1%.
5. Conclusion
Aiming at the parameters of a recoil mechanism of a small caliber gun, combing with the measurement and genetic algorithm, the parameters of the recoil mechanism for the rigid-flexible coupling launch dynamics model were corrected based on the time-domain response method. The difference of the maximum value of the recoil displacement between the simulation and measurement was reduced from 9% to 0.1%, and the similarity of the recoil displacement curves of the simulation and the measurement reached 0.99. The updated result based on the time-domain response effectively increased the accuracy of the dynamics model of the recoil mechanism, and made the dynamics model can more accurately reflect the dynamic characteristics of the recoil mechanism. Thus the updating result is useful for ensuring the simulation accuracy of the launch dynamics model.

References
[1] Tan Lebin, Zhang Xiangyan and Guan Honggen 2005 Introduction of Gun (Beijing: Beijing Institute of Technology Press)
[2] Xiao Hui, Yang Guolai and Ge Jianli 2016 Journal of Ballistics 28 2
[3] Zhang Yuelin 1984 The Design of Gun Recoil Mechanism (Beijing: National Defence Industry Press)
[4] Xu Xiuzhong, Zhang Zhiyi and Hua Hongxing 2003 Journal of Vibration Engineering 16 3
[5] H Sarin, M Kokkolaras and G Hulbert 2010 Measurement and Control 132 16
[6] J Zapico Valle and R Alonso Camblor 2010 Mechanical Systems and Signal Processing 24 7
[7] Zhang Jinzhong, Su Zhongting and Xu Da 2014 Journal of Gun Launch & Control 35 1
[8] Zhou Le, Yang Guolai and Ge Jianli 2015 Acta Armamentar II 36 3
[9] Zong Shizeng, Qian Linfang and Xu Yadong 2007 Acta Armamentar II 28 3
[10] Hong Yajun, Cao Yanfeng and Yin Qiang 2013 China Mechanical Engineering 24 1
[11] Jiao Xiaojuan, Zhang Jiewei, Peng Binbin 2010 The Optimization and Simulation Technology of Multibody System base on RECURDY (Beijing: Tsinghua University Press)
[12] Bao Ziyang and Yu Jizhou 2016 Intelligence-optimized algorithms and MATLAB examples (Beijing: Publishing House of Electronics Industry)