Optimization design of structure parameters of dynamic recoil device

Peng Li1, Yongcai Chen and Yuliang Yang
Army Engineering University, 97 Heping West Road, Shijiazhuang, Hebei, China;
1 E-mail: rifle_li@hotmail.com

Abstract. The muzzle dynamic recoil device for guns was designed. The optimization of dynamic recoil device was studied in detail. Using the MATLAB optimization toolbox, a series of optimized parameters of dynamic recoil device were got. By compared the results of dynamic recoil test with live-fire of the gun, the rationality and practicability of the dynamic recoil device has been proved. It is also proved that the muzzle dynamic recoil device can meet the dynamic recoil test requirements of guns.

1. Introduction
For the guns after major repairs, the dynamic recoil test is a necessary step to check capability of components and status of recoil movement. Live-fire of guns is expensive and difficult to implement. Water shot test is a traditional method to replace live-fire. In the water shot test, a wooden stopper is used to seal the bore bottom of the gun. Then some water was infused into the bore and fired. Because of the noise and site factors, water shot test is limited in practical use. The muzzle dynamic recoil device breaks through the limit of test site. It can be used in a small field of factory or school. So it is got attention of research institutions at home and abroad. The practicability of muzzle dynamic recoil device is proved by relative researches [1, 2].

There are some methods to design muzzle dynamic recoil device. The “support gun- dynamic recoil device -test gun” scheme use one gun as the experimental station. The test gun is connected by the dynamic recoil device. The structure of dynamic recoil device is simple and the operability is good. In this study, structure parameters of such dynamic recoil device are analyzed and optimized.

2. Principle of muzzle dynamic recoil device
The principle of muzzle dynamic recoil device is shown in Figure 1. In the dynamic recoil test, the device is connected to the muzzle of support gun and test gun respectively. Put some propellant into the chamber through ignition hole. When the propellant is ignited by the ignition device, high-temperature and high-pressure gas is generated in the chamber. The gas pushes the test gun to recoil through the piston and the piston rod. When the piston passes the vent, gas in the chamber is released. The pressure of the chamber falls quickly. The buffer can stop the movement of the piston. When the test gun is separated from the piston rod, it will recoil freely. The support gun will recoil simultaneously in the test and play a role as a buffer seat. When the movement of two guns is end, they will return to the initial position respectively.
3. Interior ballistic model of dynamic recoil device

3.1. Math model of interior ballistic

Based on the classical interior ballistic theory, the math equations of interior ballistic of dynamic recoil device were established [3]. For the test gun, the equation of recoil motion is

$$\frac{dv_1}{dt} = \frac{Sp - R_1}{M_1}$$  \hspace{1cm} (1)

Where $v_1$ is the recoil velocity. $M_1$ is the recoil mass of the test gun. $S$ is the working area of piston. $p$ is the gas pressure in the chamber of dynamic recoil device. $R_1$ is the recoil resistance.

$$R_1 = \phi_{01} + P_{f1} + F_1$$  \hspace{1cm} (2)

Where $\phi_{01}$ is the resistance of recoil mechanism. $P_{f1}$ is the resistance of counter-recoil mechanism. $F_1$ is the friction.

The equation between recoil velocity and recoil length is

$$\frac{dl_1}{dt} = v_1$$  \hspace{1cm} (3)

Where $l_1$ is the recoil length of test gun.

The equation between recoil velocity, recoil work and recoil resistance is

$$\frac{dw_1}{dt} = R_1 \cdot v_1$$  \hspace{1cm} (4)

Where $w_1$ is the recoil work of the test gun.

The equation between burning speed of propellant and the gas pressure in the chamber of dynamic recoil device is

$$\frac{dz}{dt} = \frac{u_1}{e_1} \cdot p$$  \hspace{1cm} (5)

Where $z$ is the burning thickness of propellant. $u_1$ is the burning speed coefficient of propellant. $e_1$ is half the thickness of the propellant.

The motion law of support gun is similar to that of test gun. So we can write the equations of support gun directly. The math equations of interior ballistic of dynamic recoil device are shown in (6). The supplementary equations of dynamic recoil device are shown in (7).
\[
\begin{aligned}
\frac{dv_1}{dt} &= \frac{Sp - R_1}{M_1} \\
\frac{dv_2}{dt} &= \frac{Sp - R_2}{M_2} \\
\frac{dl_1}{dt} &= v_1 \\
\frac{dl_2}{dt} &= v_2 \\
\frac{dw_1}{dt} &= R_1 \cdot v_1 \\
\frac{dw_2}{dt} &= R_2 \cdot v_2 \\
\frac{dz}{dt} &= u_1 \cdot e_1
\end{aligned}
\]

\( (6) \)

\[
\begin{aligned}
p &= \frac{f \omega \psi - \frac{1}{2} \theta (M_1 v_1^2 + M_2 v_2^2 + 2w_1 + 2w_2)}{S \cdot (l_3 + l_4 + l_5)} \\
l_\psi &= \frac{W_0}{S} \left[ 1 - \frac{\omega}{W_0 \cdot \delta} - \frac{\omega}{W_0} (\alpha - \frac{1}{\delta}) \psi \right] \\
\psi &= \chi_1 \cdot z + \chi_2 \cdot \lambda_2 \cdot z^2 \\
R_1 &= \phi_{01} + P_{f1} + F_1, R_2 = \phi_{02} + P_{f2} + F_2
\end{aligned}
\]

\( (7) \)

Where \( f \) is the force of the propellant. \( \psi \) is the burning percentage of mass of the propellant.

### 3.2. Simulation model of interior ballistic

Based on equations (6) and equations (7), the numerical simulation model of dynamic recoil device was established in the MATLAB Simulink. The simulation model is shown as Figure 2.
Take a type of gun for an example, the input parameters are as follows: mass of propellant $\omega = 160$ g, volume of chamber $W_0 = 1.3$ dm$^3$, working length of piston $l = 200$ mm, area of piston $S = 2.5$ dm$^2$. The pressure-length curve of simulation is shown as Figure 3.

![Figure 3. The interior ballistic simulation result of the dynamic recoil device.](image)

### 4. Structure optimization design of dynamic recoil device

#### 4.1. Model of optimization

The strength of the dynamic recoil device depends on the pressure of chamber $p$. On the premise of meeting the requirements of recoil test, the maximum value of pressure $p$ should be kept as small as possible. So the pressure $p_{\text{max}}$ was selected as the object function of optimization.

\[
\min f(x) = p = \frac{f \omega \psi - \frac{1}{2} \theta (M_1 v_1^2 + M_2 v_2^2 + 2w_1 + 2w_2)}{S \cdot (l_\psi + l_1 + l_2)}
\]

The law of movement of the recoil device depends on some parameters as follows: the mass of propellant $\omega$, the area of piston $S$, and the relative travel of piston, or in other words the sum of travels of the support gun and the test gun $(l_1 + l_2)$. So the parameters $[\omega, S, (l_1 + l_2)]$ were selected to be the design variables. The recoil velocity of test gun $v_2$ must meet certain requirement. So $v_2$ was selected as the constraint condition. In the process of optimization, the object function is not only the function of design variables, but also the function of recoil work $w$ and the percentage of propellant burning $\psi$ and other parameters. So solving the object function is a complex process that need solve differential equations includes interior ballistic equations.

#### 4.2. Analysis of structure optimization

Using the optimization toolbox in MATLAB, the structure parameters of dynamic recoil device is optimized. This optimization is an extreme value problem of nonlinear functions with multi variables and constraint condition. So the fmincom function of optimization tool box is selected to solve the problem.
The syntax of fmincom is \([\text{endx}, \text{fval}]=\text{fmincon}(@\text{fun}_\text{ysyl}, \text{ax0}, [], [], [], \text{lb}, \text{ub}, @\text{fun}_\text{hzcd}, \text{options}).\]

The parameter \(\text{endx}\) is the output optimization value of design variables. The parameter \(\text{fval}\) is the object function value, i.e. the value of \(p_{\text{max}}\). The parameter \(\text{fun}_\text{ysyl}\) is the input object function. The parameter \(\text{ax0}\) is the initial value of design variables. The parameters \(\text{lb}, \text{ub}\) are the lower and upper limits of design variables. The parameter \(\text{fun}_\text{hzcd}\) is the constraint condition of optimization. The parameter \(\text{options}\) includes the setting parameters of optimization function.

The optimization results of dynamic recoil device structure are as follows: the mass of propellant \(\omega=168\ \text{g}\), the working area of piston \(S=2.63\ \text{dm}^2\), the relative travel of piston \((l_{\text{f}}+l_{\text{i}})=186\ \text{mm}\). The maximum value of chamber pressure \(p_{\text{max}}=231.86\ \text{MPa}\). The law of movement of the test gun meets the requirement of dynamic recoil. Also the strength of the dynamic recoil device is satisfied. The compared curves of dynamic recoil test and live-fire of one gun are shown in Figure 4.

![Recoil curve comparison](image)

**Figure 4.** The compared curves of dynamic recoil test and live-fire.

From this figure, we can see the maximum velocity of the gun in dynamic recoil test \(v_{\text{max}}=11.66\ \text{m/s}\). The maximum recoil length of the gun \(\lambda_{\text{max}}=852.62\ \text{mm}\). As a contrast, the maximum velocity of the gun in live-fire \(v_{\text{max}}=10.17\ \text{m/s}\). The maximum recoil length in live-fire \(\lambda_{\text{max}}=875.24\ \text{mm}\). The maximum recoil length error between dynamic recoil test and live-fire is 2.58%. For the dynamic recoil test of the guns, the maximum recoil length is a key parameter because it determines whether the gun works properly or not. When the error between dynamic recoil test and live-fire is less than 10%, we can judge that the test is successful. The above results show that the dynamic recoil test and the live-fire coincide with each other.

5. **Conclusions**

By changing the connection device between the dynamic recoil device and the gun, the dynamic recoil device can be used in different caliber guns. We also can change the mass of propellant to get different maximum recoil lengths to make the dynamic recoil test consistent with the live-fire of the gun. Therefore, the dynamic recoil device can be used in different occasions. And the force analysis of gun tube shows that the maximum stress in gun barrel is 21.25 MPa in the recoil test [4]. Which means both the strength and bending degree of the gun tube can be able to meet the requirements. The dynamic recoil test has no damage to the gun barrel. The muzzle dynamic recoil device has the
advantages that the structure is simple, the weight is light, and the use is convenient. Only a small quantity of propellant is needed in the dynamic recoil test. The noise and danger of the test are very small and therefore the test process has little impact on the environment. In a word, beyond live-fire and water shot test, the muzzle dynamic recoil device provides a practical and convenient technical means for gun’s test after major repairs.

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