Research on Unmanned End-effector and Its Buffer Parameters

Zhe Zeng\textsuperscript{1,a}, WenBo Shi\textsuperscript{2,b}, YangYang Hou\textsuperscript{2,c}, HuaJie Hong\textsuperscript{3,d,*}

\textsuperscript{1}College of Intelligence Science and Technology, National University of Defense Technology, Changsha, Hunan, China
\textsuperscript{2}63601 Unit of People’s Liberation Army, Jiuquan, Gansu, China
\textsuperscript{3}College of Intelligence Science and Technology, National University of Defense Technology, Changsha, Hunan, China
\textsuperscript{4}College of Intelligence Science and Technology, National University of Defense Technology, Changsha, Hunan, China
\textsuperscript{a}email: zengzhe@nudt.edu.cn
\textsuperscript{b}email: 1506799262@qq.com
\textsuperscript{c}email: houyangyang14@nudt.edu.cn
\textsuperscript{d}email: honghuajie@nudt.edu.cn

Corresponding author: *demail: honghuajie@nudt.edu.cn

Abstract: Based on the future application of integrated reconnaissance and strike of small unmanned combat platform, the parameters of terminal strike weapon and terminal buffer mechanism are designed and analyzed in this paper. Firstly, the internal ballistic simulation of the terminal strike load is carried out and verified with the experimental results. Then, the buffering system is modeled, the buffering parameters are analyzed theoretically and the local optimal solution is analyzed, the general law of the local optimal solution is obtained, and the optimal solution is obtained. Finally, the simulation is carried out.

1. Introduction
In recent years, urban anti-terrorism operations have received more and more attention, and the forms of urban anti-terrorism operations have become more and more diverse. The use of small unmanned combat units such as unmanned aerial vehicles and unmanned vehicles is becoming increasingly common. However, the main purpose of small combat units is reconnaissance, and a single function is very disadvantageous for the ever-changing battlefield. For the future battlefield, small unmanned combat units need to be able to integrate reconnaissance, communications, exploration, and firepower strikes in order to play a role in a narrower and more complex environment. According to the above concept, an unmanned system with a pistol at the end of a small unmanned vehicle as a strike load and a robotic arm as a connection and movement device can carry different end loads according to different mission requirements, which can well integrate reconnaissance and strikes. Firstly, compared with traditional small unmanned combat units, such small unmanned units can adopt various cluster tactics, and can quickly survey and survey terrain in urban operations, strike targets in real time, and gain an advantage in quantity. Secondly, compared to traditional end-strike loads such as machine guns, pistols...
have the advantages of more flexibility, greater versatility, higher precision, and faster speed. Therefore, the design of such unmanned units is very necessary, and it is closer to actual combat. This paper mainly focuses on the design and analysis of the unmanned terminal strike load design and the parameters of the buffer device.

2. Materials and Methods

With the advancement of industrialization, mechanical arm has been widely used in various fields by virtue of its high degree of freedom, high flexibility and convenient control. In the field of unmanned platform, the robot arm is mainly used for grasping and explosive disposal. Combined with the above advantages, this paper proposes to complete the design of the end effector of the unmanned platform by using the robot arm as the front end of motion and a certain type of pistol and compliant buffer mechanism as the end effector.

In the process of operation, the end-effector is inevitably affected by various dynamic excitation, among which the recoil impact load has the most serious impact on the structure. Gun will produce high speed, intermittent and repeated impact force in the process of shooting. Although the weapon itself takes measures to reduce recoil design, the residual recoil force is still very large. The continuous impact of recoil force on the structure will affect the dynamic performance and shooting accuracy of the system, and even cause damage to the structure. Therefore, the recoil force analysis and research of the weapon load should be carried out first to design the buffer device. Second in order to ensure the stability and shooting accuracy, shooting should meet weapons and equipment miniaturization, lightweight, high integration, high precision and dynamic performance demand.

2.1 Guns recoil analysis

A type of pistol has the advantages of simple structure, complete function and strong fire persistence. This type of pistol adopts semi-free gun automatic mode, relying on the gun recoil, complete the opening of the gun chamber, pull out and throw out the cartridge case, and at the same time re-enter the spring to absorb the stored energy. The energy stored by the compound spring is used to complete the thrusting motion. Internal ballistics is a subject which studies the motion law of the projectile in the chamber and a series of shooting phenomena accompanying it. That is, given the gun chamber structure elements (such as chamber volume, projectile travel.) and loading conditions (such as charge mass, projectile mass, shape and nature of gunpowder) to calculate the gas pressure change law and projectile motion law in the chamber. According to the basic equation of the interior ballistic, the interior ballistic curve $p - t$ and $v - t$ are solved, and then the recoil impulse of the gun is solved according to the pressure-displacement curve (for the recoil buffer of the gun, the analysis of the recoil force of the gun is of no practical significance, so the design and analysis should be carried out according to the recoil impulse of the gun), so as to design the buffer.

The equations of interior ballistics in classical interior ballistics are based on the following basic assumptions:

- Gunpowder combustion follows geometric combustion law.
- The pellets burn under average pressure and follow the law of combustion rate.
- The heat loss on the inner chamber surface can be indirectly corrected by reducing the fire power or increasing the specific heat ratio.
- Use coefficients to consider other secondary elements.
- The extrusion of the projectile belt into the rifling is instantaneous, and a certain extrusion pressure marks the starting condition of the projectile.
- The dynamical force obeys the Nobel-Abier equation of state.
- The energy released by the combustion of gunpowder per unit mass and the combustion temperature of the generated gas are both fixed values. In the subsequent expansion process, the change of gas components is not taken into account. Therefore, although the temperature of the gas decreases due to expansion, the explosive force, residual capacity and specific heat ratio are all regarded as constants.
8) After the projectile belt is squeezed into the rifling, it is well sealed and there is no air leakage phenomenon.

Establishment of interior ballistic equations:

\[ \psi = \chi Z (1 + \lambda Z + \mu Z^2) \]  
(1)

\[ \frac{dZ}{dt} = \frac{u_1 p^n}{\epsilon_1} \]  
(2)

\[ \phi m \frac{dv}{dt} = Sp \]  
(3)

\[ Sp(l_o + l) = f \omega \psi - \frac{\theta}{2} \phi mv^2 \]  
(4)

\[ l_\psi = l_o [1 - \frac{\Delta}{\rho_p} (1 - \psi) - \alpha \Delta \psi] \]  
(5)

\[ \theta = k - 1 \]  
(6)

Among them:

\[ \frac{dl}{dt} = v \]  
(6)

| \( \psi \) | percentage of gunpowder already |
| \( \chi \) | powder shape characteristic |
| \( \lambda \) | gunpowder has relative thickness |
| \( \mu \) | time |
| \( t \) | burning rate constant |
| \( p \) | bore pressure |
| \( n \) | burning rate index |
| \( e_1 \) | arc thick |
| \( I_k \) | total impulse of pressure at the end of combustion of gunpowder |
| \( \varphi \) | the coefficient of secondary work |
| \( m \) | the quality of the projectile |
| \( v \) | the projectile velocity |
| \( S \) | the cross sectional area of the bore |
| \( l_0 \) | chamber volume shrink neck length |
| \( \Delta \) | loading density |
| \( \rho_p \) | density of gunpowder |
| \( \alpha \) | residual volume of gunpowder gas |
| \( l \) | the projectile trip |
| \( f \) | impetus |
| \( \omega \) | charging quality |
| \( k \) | adiabatic index |

After simplification of the above equation, the first-order differential equations of \( P, v, l, Z \) can be obtained, and the fourth-order fixed-step Rong-Kung method can be used to calculate them:
For a system of first order differential equations:

$$\begin{align*}
\frac{dy_i}{dx} &= f_i(x, y_1, y_2, \cdots, y_n) \\
y_i(x_0) &= y'_0
\end{align*}$$

i = 1, 2 \cdots n \tag{7}

Fourth-order Rong-Kung formula:

$$y_{i,k+1} = y_i + \frac{h}{6} (K_{i1} + 2K_{i2} + 2K_{i3} + K_{i4}) \\
i = 1, 2 \cdots n \tag{8}
$$

where step size $h = x_{k+1} - x_k$

$$\begin{align*}
K_{i1} &= f_i(x_k + hy_{ik1}, \cdots, y_{nk}) \\
K_{i2} &= f_i(x_k + \frac{h}{2}y_{ik2} + \frac{hK_{i1}}{2}, \cdots, y_{nk} + \frac{hK_{i1}}{2}) \\
K_{i3} &= f_i(x_k + \frac{h}{2}y_{ik3} + \frac{hK_{i2}}{2}, \cdots, y_{nk} + \frac{hK_{i2}}{2}) \\
K_{i4} &= f_i(x_k + h, y_{ik4} + hK_{i3}, \cdots, y_{nk} + hK_{i3})
\end{align*} \tag{9}
$$

The variation law of recoil impulse with time can be calculated according to the basic solution of interior ballistic:

$$I = \int_0^{t_f} P(t) \cdot S_d \cdot dt = m(v_2 - v_1) \tag{10}$$

Where $I$ is the impulse generated by the recoil force, $t_0$ is the action time of the recoil force, $m$ is the quality of the gun assembly, $v_2$ is the starting speed of the gun recoil, and $v_1$ is the speed of the gun recoil in place. According to the fact that the action time of impact force is far less than the natural period of the isolation system and the amplitude of impact response appears after the end of impact force, the impact response can be equivalent to velocity step. Then the above formula can be used to calculate the initial velocity step, which provides input for the calculation of buffer parameters in the following paper.

2.2 Research and analysis of buffer parameters

2.2.1 Problems in modeling

The end-effector is transformed into a single degree of freedom free vibration system.

The equation of state of the system satisfies formula (11):

$$m\ddot{x} + c\dot{x} + kx = 0 \tag{11}$$

Initial condition satisfies formula (12):

$$x(0) = 0, \dot{x}(0) = v_0. \tag{12}$$

General properties of automatic weapon station constraint index usually contains: maximum impact
limit, quick resilience restrictions and maximum displacement constraints, for the actual situation for a
certain type of gun and the maximal displacement limit maximum limit recoil (usually transformed into
maximum acceleration limits), usually two functional indexes are used to describe the two constraints:

\[ J_1 = \max_t \left| x(t) \right| \]
\[ J_2 = \max_t \left| \dot{x}(t) \right| \]  

As necessary, the current problem is when \( J_1 = D_a \), minimize \( J_2 \).

2.2.2 Parametric analysis and optimization
The displacement response of the system is solved as:

\[ x(t) = \frac{v_0}{\omega_d} e^{-\xi \omega_n t} \sin \omega_d t = \frac{v_0}{\omega_n \sqrt{1 - \xi^2}} e^{-\xi \omega_n t} \sin \omega_d t \]  

where \( \omega_n = \sqrt{\frac{k}{m}} \) is the natural frequency of the system, \( \xi = \frac{c}{2\sqrt{mk}} \) is the damping ratio of the system, 
\( \omega_d = \sqrt{1 - \xi^2} \omega_n \) is the attenuation frequency of the system.

\[ \ddot{x}(t) = \frac{v_0 \omega_n}{\sqrt{1 - \xi^2}} e^{-\xi \omega_n t} \sin(\omega_d t - \beta) \]
\[ \beta = 2 \arctan \left( \frac{1 - \xi^2}{\xi} \right) \]  

Because of the phase, the absolute value of the maximum acceleration response of the system can
only occur at time zero or at the first extreme value, which can be obtained by comparison:
when \( 0 < \xi < 0.5 \):

\[ \ddot{x}_{max} = \left| v_0 \right| \omega_n e^{-\xi \omega_n t} \frac{\pi - 3 \arctan \left( \frac{1 - \xi^2}{\xi} \right)}{\sqrt{1 - \xi^2}} \]  

when \( 0.5 < \xi < 1 \):

\[ \ddot{x}_{max2} = 2\xi \left| v_0 \right| \omega_n \]  

The relation between peak recoil acceleration index \( J_2 \), damping ratio \( \xi \) and natural frequency\( \omega_n \)
is analyzed. According to the above equation, the acceleration characteristic curve of the impact response of the velocity step buffer system can be obtained as shown in Figure 3.
The acceleration and velocity can be obtained by taking the machine:

\[ x_{\text{max}} \cdot \dot{x}_{\text{max}} = \begin{cases} 
\frac{\xi}{\sqrt{1-\xi^2}} \left( \pi - 4 \arctan \frac{1-\xi^2}{\xi} \right) v_0^2 e^{1-\xi^2} & (0 \leq \xi \leq 0.5) \\
2\xi v_0^2 e^{1-\xi^2} & (0.5 < \xi < 1) 
\end{cases} \]  

(20)

As we can see, when the damping ratio is selected, for the single degree of freedom linear free vibration system, when the impact velocity response is determined, the product of the maximum acceleration and maximum displacement is constant, and the two are inversely proportional, one of the parameters can be determined to optimize the other parameter, and there is an extreme value of any of the parameters. Therefore, the required stiffness and damping ratio of the system can be determined by calculating the acceleration at the extreme value:

\[ J_{\text{2min}} = \begin{cases} 
\frac{v_0^2}{D_0} e^{1-\xi^2} \left( \pi - 4 \arctan \frac{1-\xi^2}{\xi} \right) & (0 \leq \xi \leq 0.5) \\
2\xi \frac{v_0^2}{D_0} e^{1-\xi^2} - \frac{\xi}{\sqrt{1-\xi^2}} & (0.5 < \xi < 1) 
\end{cases} \]  

(21)

Through the extremum, the optimal impact resistance can be obtained:

\[ J_2 = 0.52 \frac{v_0^2}{D_0} \]  

(22)

\[ k = \frac{0.36 m v_0^2}{D_0} \]  

(23)

\[ c = \frac{0.49 m |v_0|}{D_0} \]  

(24)

3. Results & Discussion

3.1 Simulation and data analysis of pistol interior ballistic system

Based on the basic equation of interior ballistics, the curve of interior ballistics \( p - t, \ v - t \) are solved.
The experimental results of data simulation are compared with those of dynamic simulation as shown in Table 2.

| Content                  | Simulation  | Experimental | Error(%) |
|--------------------------|-------------|--------------|----------|
| Start speed by recoil    | 5.87 m/s    | 6.15 m/s     | 4.55     |
| Recover end speed        | 3.96 m/s    | 4.01 m/s     | 1.25     |
| Recoil impulse.          | $1.516 \times 10^6 g \cdot mm/s$ | $1.451 \times 10^6 g \cdot mm/s$ | 4.54     |

As can be seen from the table, the data obtained from simulation are in good agreement with the firing test data when the pistol is fixed on the gun rack, with errors less than 5%, which meets the needs of engineering calculation. Moreover, the equivalent velocity step can be obtained according to Equation (10).

3.2 Theoretical research on buffer system

When designing the buffer system, first of all, to prevent the resonance, it must ensure that its natural frequency is greater than the firing frequency, next according to $f_2$ and $\xi$, the relationship curve of $w_n$ shows that the peak acceleration of buffer system will decrease with the increase of damping, which means that the biggest will reduce the heritability, according to the formula can also be concluded that with the increase of system natural frequency, acceleration of buffer system will also increase.

According to the buffer stiffness and damping designed above, the velocity displacement curve of the buffer system can be obtained as shown in Figure 5.
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Figure 5 Displacement response curve

It can be seen that the maximum displacement is less than the limit of the maximum displacement, in line with the design requirements.

4.Conclusion
This paper in view of the small unmanned combat platform at the end of the actuator for the buffer parameter design and analysis, first of all, we according to the basic equation of interior ballistic pistol in the back seat of the basic parameters for the simulation analysis, it is concluded that the basic pressure time curve and the bolt recoil speed - displacement curve, and compared with the experimental data verify the validity of the equation.

Secondly, according to the basic law of the buffer model, we design and optimize the buffer parameters, and analyze the damping ratio and the maximum recoil force on the basis of the determined maximum recoil displacement, there is a local minimum value, in other words the maximum recoil at maximum recoil displacement under the condition of a given local optimal solution, and can according to the parameters of stiffness and damping design analysis.

In this paper, the design and analysis of recoil buffer parameters can provide a theoretical basis for the later design of buffer stiffness mechanism, and have reference value for the design and research of end-effector in the future.

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