Research on recoil dynamic characteristics of a gatling gun automatic machine

Yifang Sun, Li Li and Feng Xie
Zhengzhou Electromechanical Engineering Research Institute, Zhengzhou 450015, China
E-mail: syf001030@163.com

Abstract. This paper takes an aerogun automatic machine as the research object, and uses the classical internal ballistic theory to establish a mathematical model for calculating the bore resultant force. The fourth-order Runge-Kutta solution is used to calculate the average pressure-time curve in the internal ballistic and after-effect period. The automatic machine virtual prototype model is established by using the 3D model of the automatic machine and the calculation result of the bore resultant force, and the recoil displacement, recoil velocity and recoil force of the automatic machine are obtained, which provides a theoretical basis for the subsequent research and design of the automatic machine.

1. Introduction
The recoil dynamic characteristic of automatic machine is an important index to evaluate the performance of aerogun. During the shooting of aerogun, the gunpowder gas will produce a backward bore resultant force acting on the automatic machine, which will cause the automatic machine to accelerate backwards. Through the action of the buffer device, the bore resultant force of short action and large peak can be converted into a small force and transmitted to the gun rack, which can effectively control the force and movement of the gun and create conditions for improving the rate of fire and ensuring the reliability of the gun rack[1,2].

2. Calculation of bore resultant force and establishment of virtual prototype

2.1 Calculation of internal ballistic
In the calculation of internal ballistic, the following steps are generally followed to solve the internal ballistic equations: 1) establish a mathematical model; 2) select the fourth-order Runge-Kutta method to solve the internal ballistic equations; 3) write internal ballistic solver; 4) calculate the equations. According to the motion process of the projectile in the gun bore and the combustion law of gunpowder, the internal ballistic is divided into three periods for calculation, which are respectively the early period of the internal ballistic, the first period of the internal ballistic and the second period of the internal ballistic. After the projectile leaves the muzzle, the gas pressure in the bore still exists and is very high, so the effect of the after-effect period should be taken into account in the calculation of the pressure in the bore.

Taking the single barrel of aerogun automatic machine as the research object and combining with the mathematical model of internal ballistic and after-effect period, the average pressure in the bore in each period is calculated in MATLAB. After calculation, the bore pressure-time curve of internal ballistic and after-effect period are shown in figure 1 below:
2.2 Calculation of bore resultant force

Bore resultant force is generally divided into start-up period, gun bore movement period and after-effect period of gunpowder gas, among which start-up period is generally replaced by starting pressure. According to the bore pressure-time curve of internal ballistic and after-effect period, the bore resultant force of the gun bore movement period and after-effect period of gunpowder gas can be calculated. The expression is:

\[ F_{pt} = \begin{cases} 
  Ap\left(1 + \frac{\omega}{2m}\right)l(\varphi_1 + \frac{\omega}{3m}) & (0 \leq t < t_g) \\
  Ap_g\left(\varphi_1 + \frac{\omega}{2m}\right)l(\varphi_1 + \frac{\omega}{3m}) & (t = t_g) \\
  Ap_g e^{-b(t-t_g)}\left(\varphi_1 + \frac{\omega}{2m}\right)l(\varphi_1 + \frac{\omega}{3m}) & (t_g < t \leq t_k) \\
  0 & (t > t_k) 
\end{cases} \]  

in this equation: \( m \) —the projectile mass, \( \omega \) —the charging mass, \( \varphi_1 \) —the sub-important power coefficient that only considers the projectile rotation and friction, \( A \) —the bore area, \( P \) —the average pressure in the bore, \( p_g \) —the average pressure in the bore when the projectile leaves the muzzle, \( b \) —the time constant reflecting the decay rate of the bore resultant force, \( t_k \) —the time when the projectile leaves the muzzle, \( t_k \) —the time when the after-effect period ends.

2.3 Establishment of automatic machine virtual prototype

In the establishment of the virtual prototype model, the automatic machine is first modeled by the 3D modeling software, and then the 3D model of the automatic machine is imported into the working environment of ADAMS for simulation calculation [3].

a) Establishment of automatic machine curve groove model

The cam curve groove of the automatic machine is the core component. The shape characteristics of the cam curve groove determine the dynamic characteristics of the automatic machine. Therefore, the establishment of the cam curve groove 3D model is very important to the study of automatic machine dynamic law.

Firstly, the points on the cam curve groove of the automatic machine prototype are measured, and a total of 6300 sets of data including the coordinate values in the horizontal and vertical directions are obtained, as shown in figure 2.
Then the coordinate data of these points is written into the IBL data file in CREO, and the data points in the IBL data file are fitted by the B-spline fitting curve in CREO, therefore the spline curve of the cam curve groove along the middle diameter is obtained. Scanning the curve can obtain the shape of the cam curve groove along the middle diameter, and the curve groove model is obtained by circularly bending the curve groove body obtained by scanning, as shown in figure 3.

![Figure 3. Curve groove 3D model.](image)

b) Establishment of other component models of automatic machine

The 3D model of the automatic machine is obtained by modeling the 3D solids of other components of the automatic machine in CREO as shown in figure 4.

![Figure 4. 3D model of an aerogun automatic machine.](image)

2.4 Define Constraints

The connection and relative motion between components in the virtual prototype model are defined by constraints. In ADAMS, constraints generally have the following five forms: ideal constraint, basic constraint, contact, drive and load.

a) Define ideal constraint

The dynamics simulation of the whole automatic cycle process of the aerogun automatic machine is carried out to obtain the dynamic characteristics of the main components of the automatic machine during the movement. Appropriate constraints are added between the moving components of the automatic machine virtual prototype based on the actual constraints between the components. The constraint relationship between the components of the automatic machine is shown in table 1.
Table 1. The main joints between the components of automatic machine.

| Component A | Component B | Joints     | Component A | Component B | Joints     |
|-------------|-------------|------------|-------------|-------------|------------|
| Barrel      | Breech      | Fixed      | Piston rod  | Cylinder    | Translational |
| Cylinder    | Barrel      | Fixed      | Breech      | Gun box     | Revolute   |
| Gun box     | Cradle      | Translational | Buffer spring | Gun box | Translational |
| Curve groove | Gun box    | Fixed      | Star body   | Breech      | Fixed      |
| Bevel gear  | Star body   | Fixed      | Breechblock | Star body   | Translational |
| Feeding wheel | Feeding wheel | Fixed       | Feeding wheel | Gun box     | Revolute   |
| Intake cover | Gun box     | Fixed      | Crank       | Connecting rod | Inline |
| Connecting rod | Piston rod | Revolute    | Barrel      | Clamp       | Fixed      |
| Unlock device | Gun box     | Fixed      | Lock device | Gun box     | Fixed      |
| Projectile  | Star body   | Translational | Projectile | Barrel      | Translational |
| Rear cover  | Crank       | Revolute    | Rear cover  | Gun box     | Fixed      |
| Support frame | Ground     | Fixed      | Support frame | Gun box     | Translational |

b) Define contact

Contact can be seen as a special constraint, such as the mutual contact between the breechblock and the curve groove in the automatic machine, the mutual contact between the feeding wheel and the projectile. In the virtual prototype, a contact force is applied between the components that are in contact with each other, and the form of the contact force is calculated by the IMPACT function algorithm [4,5]. The contacts in the automatic machine virtual prototype model are shown in table 2.

Table 2. The contact relationship of automatic machine virtual prototype.

| Component A | Component B | Joints     | Component A | Component B | Joints     |
|-------------|-------------|------------|-------------|-------------|------------|
| Projectile  | Feeding wheel | Contact   | Projectile  | Bottom guideway | Contact |
| Projectile  | Breechblock head | Contact   | Curve groove | Breechblock wheel | Contact |
| Breechblock head | Lock device | Contact   | Breechblock head | Unlock device | Contact |
| Breechblock head | Breech | Contact   | Firing sensor | Breechblock head | Contact |
| Crank       | Bevel gear  | Contact   | Projectile  | Ejection wheel | Contact |
| Breechblock head | Star body | Contact   | Support frame | Gun box     | Translational |

c) Define load

According to the working principle of the automatic machine, in the dynamic simulation, it is necessary to add the bore resultant force generated by the gunpowder gas to the automatic machine, and it is necessary to add a buffer spring force to realize the recoil cushioning of the automatic machine.

1) Add bore resultant force to the automatic machine virtual prototype

During the automatic machine shooting process, with the rotation of the barrel group, the bore resultant force acts on the tail portion of the automatic machine. Due to the high rotation speed of the barrel, the bore resultant force of the adjacent barrels may be superimposed. In the study of the automatic machine curve groove dynamics and the automatic machine recoil dynamics, it is necessary to accurately add the bore resultant force to the automatic machine virtual prototype model at the required firing position and firing time.

2) Processing of the buffer spring

In the analysis of the recoil dynamic characteristics of the automatic machine, it is necessary to add a recoil buffer spring to provide the recoil resistance for the automatic machine virtual prototype model. Taking the recoil part of the automatic machine as the research object, it mainly bears the bore resultant force during the shooting of the automatic machine, the recoil resistance during the back cushioning and the friction during the movement.

In order to accurately simulate the recoil dynamic characteristics of the automatic machine, it is necessary to determine the structural parameters of buffer spring such as the type, stiffness and pre-stress [6]. This type of aerogun uses a rectangular spiral spring to realize the overall recoil cushioning motion of the automatic machine. The loading stiffness and the unloading stiffness are the same, and the front and rear ends of the buffer spring are compressed. The application of the buffer spring force
during the recoil process is implemented in the ADAMS using the Spring-Damper Force method in Flexible Connections.

3. Automatic machine recoil dynamics calculation

3.1 Initial condition setting

In order to simplify the simulation, this paper no longer fits the driving function of the automatic machine, and directly adds a constant speed of 12000 deg/s (6000 rds/min) to the bevel gear of the power component of the automatic machine virtual prototype. The automatic machine is composed of two identical buffer springs in parallel. The stiffness of a single buffer spring ($K$) is 4000N/mm, and the pre-pressure ($F_0$) is 20000N.

The type of buffer spring of automatic machine is rectangular spiral buffer spring, and the buffer spring force provided in working process can be expressed as:

$$ F_R = Kx + F_0 $$

(2)

$x$ is the working distance of buffer spring in this equation.

3.2 Result of simulation

The dynamic simulation of the automatic machine virtual prototype is carried out, and the recoil displacement, recoil velocity and recoil force of the automatic machine are obtained as shown in figure 6, 7 and 8.

According to figure 6, the peak value of recoil displacement of the automatic machine is 7.5mm and the peak value of the forward displacement is 5mm.
Figure 7. Recoil velocity of the automatic machine.

According to figure 7, the peak value of recoil velocity of the automatic machine is 1755mm/s, and the peak value of the forward velocity is 2177mm/s.

Figure 8. Recoil force of the automatic machine.

Figure 8 shows that the peak value of recoil force of the automatic machine is 28000N.

4. Conclusion
According to the classical interior ballistic theory and the fourth-order Runge-Kutta solution method, the average pressure-time curve in the bore during the interior ballistic period and the after-effect period is calculated, and the bore resultant force of the gun bore movement period and after-effect period of gunpowder gas is obtained. The automatic machine virtual prototype model is established and the bore resultant force and buffer spring force are added to it. The recoil displacement, recoil velocity and recoil force of the automatic machine is obtained, which provides a theoretical basis for the subsequent research and design of the automatic machine.

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