Coupling characteristics of a new automatic artillery power system

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Abstract: A new automatic artillery adopted hydraulic system as auxiliary power to solve the problem of insufficient power after unified power. Firstly, the structure and working principle of the automatic artillery were analyzed. Secondly, in order to confirm the working torque of auxiliary power, the dynamic simulation model of the new automatic artillery was established. The accuracy of the simulation model was verified by test. The effect of output torque of auxiliary power system on the firing rate and roller bearing was researched, based on the simulation model. Finally, the working characteristics of the auxiliary power system were analyzed, and the design of the auxiliary power system was carried out.

1. Introduction
A new type of automatic gun, after achieving faster firing rate by adopting the working principle of air-guided revolver, brings in the uniform power mode, and links the launching system with the ammunition feed system via gears to realize the synchronous control of the launching system and the launching system. However, uniform power will result in lower firing rate of the launching system caused by increasing load.

The launching system of one small-bore gun made in China takes gunpowder gas as the source of power, the linkless ammunition feed method as ammunition feed system, and it is driven by the motor. In order to achieve the power matching between the launching system and the ammunition feed system, a spring motor assembly [1] is added between the launching system and the ammunition feed system. French single-barrel 100mm naval gun can synchronously control the launching system and the ammunition feed system via electric control, and then achieve the power matching between the launching system and the ammunition feed system [2].

However, the spring motor’s output torque is small, and the power matching via electric control is not quite reliable. It’s impossible for this new type of automatic gun to borrow advantages of the above mentioned power system due to heavy ammunition and high firing rate. Targeting at the insufficient power upon applying the uniform power, the author proposes to add an auxiliary power transmission unit- hydraulic system into the ammunition feed system. Such auxiliary power transmission unit can make up the power shortage caused by uniform power and the dynamic coupling of the launching system. Furthermore, such auxiliary power transmission unit can drive the ammunition feed system to rotate and then assist to complete the ammunition loading.

2. Structure Characteristics and Working Principles of Automatic Gun
A new type of automatic gun consists of the launching system and ammunition feed system, with the launching system mainly comprising barrel, air-guided device, revolving body, recoil spring and...
feeding mechanism, as shown in Figure 1. The working principles of the launching system is as below: function the gunpowder gas on the chamber-revolving slide via the air-guided device, push the slide to move backwards, the slide’s curve groove can drive the revolving body to rotate via functioning with the revolving body’s roller, and the chamber-revolving slide will compress the recoil spring; after the chamber-revolving slide’s recoil is in place, the slide will move forward under the effect of the recoil spring, the curve groove on the other side of the slide will function with the roller to push the revolving body to rotate, and then drive the ammunition booster of the feeding mechanism to next ammunition position[3][4]. The ammunition feed system mainly comprises the hydraulic system, drive system and ammunition booster. Since the last level of ammunition booster of the ammunition feed system is linked to the ammunition booster of the feeding mechanism of the launching system via gears, therefore, the power of the launching system can drive the ammunition feed system to rotate via gears.

Figure 1 Structural Diagram of Launching System

In order to achieve the dynamic coupling between the launching system and the ammunition feed system, the hydraulic system is applied as an auxiliary power system in the ammunition feed system. When firing, upon the control system issues the strike command, the ammunition feed system’s hydraulic motor will start firstly. But considering that the launching system has not started rotating, the hydraulic motor’s output torque comes to the largest since the hydraulic motor is under locked rotor conditions due to excessive load. When the revolving body starts to move, the launching system’s speed gets faster than the motor’s speed due to the relatively high initial acceleration, with the hydraulic motor being dragged. When the motor’s speed gets faster than launching system’s speed, the hydraulic motor will push the ammunition feed system to rotate to reduce the launching system’s load resistance, and the launching system’s acceleration will speed up until the launching system’s speed equals to the motor’s speed. However, when the hydraulic motor’s operation torque is excessive, the wear of the launching system’s revolving body roller will be exacerbated, while small operation torque cannot tackle the low firing rate caused by the uniform power. As a result, the author needs to determine the operation torque via simulation and test analysis.

3. Determination of Auxiliary Power Operation Torque

3.1 Establishment and verification of automatic gun’s simulation model

3.1.1 Simplification of simulation model
The author simplifies the gun model according to the structure characteristics of automatic guns and movement rules during the firing cycling process:

1) Add the ammunition feed system’s rotational inertia into the launching system’s feeding mechanism output shaft;
2) Carry out the rigidity processing on members except springs;
3) The gun fires by driving the chamber-revolving slide to move with gunpowder air. During the
simulation, calculate the acting force of gunpowder gas as an equivalent concentrated force, and impose it on the end face of the chamber-revolving slide. The pressure of gunpowder gas in the gas port will vary over time.

The computational formula is as below:

$$P_s = P_0 e^{\frac{-t}{a}} (1-e^{-\frac{t}{b}})$$

In which:

- $P_0$ refers to the average pressure inside the chamber at the moment when the projectile passes through the gas port, expressed in $p$;
- $t$ refers to the air-chamber pressure working time from the moment when the projectile passes through the gas port, expressed in $s$;
- $a$ refers to the structural coefficient related to the air-guided device, expressed in $a = \frac{1}{b}$;
- $b$ refers to the time factor related to the pressure impulse inside the chamber, expressed in $b = \frac{t}{P_0}$.

The calculated changes of pressure of gunpowder gas in the gas port over time are as shown in Figure 2:

1) Simulation model

The virtual prototype’s simulation model established according to the movement characteristics and kinematic relationship of guns is as shown in Figure 3.

3.1.2 Experimental verification of simulation model

1) Experimental verification

Based on the above simulation model, the author sets the ammunition feed system’s rotational inertia to be 0, and the auxiliary power output torque to be 0, the recoil replacement curve of the chamber-revolving slide is as shown in Figure 4.
Moves Alone

The physical experimental test data is as shown in Table 1.

| Parameter Index | Test results |
|-----------------|--------------|
| Recoil replacement | 280mm |
| Recoil duration | 0.09s |
| Counter-recoil duration | 0.1s |

Compared with the experimental test results, the replacement simulation data of chamber-revolving slide is close the experimental test data, which means that the simulation model is relatively consistent with the practical conditions and also verifies the validity of the simulation model.

When the ammunition feed system’s rotational inertia is set to be 5kg.m², and the auxiliary power output torque is set to be 0, the recoil replacement curve of the chamber-revolving slide is as shown in Figure 6. As we can see, when the launching system is linked to the ammunition feed system, its recoil and counter-recoil duration extends to 0.23s, and the firing rate decreases from 300 rounds/minute to 260 rounds/minute. Considering the limited decrease of the firing rate, auxiliary power can be adopted to settle the decreasing firing rate caused by the uniform power.

3.1.3. Determination of automatic gun’s auxiliary power system’s operation torque

Based on the simulation model, the author imposes different torques on the ammunition feed shaft (changes of M1, M2 and M3 as shown in Figure 6) as auxiliary power for simulation analysis, and obtains the recoil replacement curve of the chamber-revolving slide and roller load-carrying curve, as shown in Figure 7 and Figure 8.
According to the simulation results, when the torque is M2 and M3, the recoil and counter-recoil duration of chamber-revolving slide is less than 0.2s. However, along with the increase of torque, the maximum load borne the roller during the counter-recoil process will increase from 40,000N to 45,000N. In summary, when the motor’s output torque gets 200–400NM, the recoil and counter-recoil duration is less than 0.2s, with the load borne by the roller being the minimum.

4. Design of Auxiliary Power System

4.1. Design of auxiliary powder system
When the launching system drives the ammunition feed system to rotate, the hydraulic system has to pump oil to the hydraulic motor quickly, otherwise, the hydraulic motor will be dragged by the launching system to move. As a consequence, the launching system’s firing rate gets slow, and the decreasing oil pressure in the motor’s fuel inlet will result in cavitation in the motor, thus severely undermining the service life of the motor. Since the hydraulic power unit is a little far away from the hydraulic motor, and the hydraulic power unit alone fails to supply oil to the hydraulic motor timely. As shown in Article 2.2, the hydraulic motor’s output torque shall vary from 200 to 400NM. The principles of hydraulic system designed by taking into consideration the above analysis are shown in Figure 9. The energy accumulator in the system can, by constantly saving and quickly releasing the pressure oil, meet the requirements of large transient flow rate and constant torque in the system.
When preparing for firing, the hydraulic power unit starts to work firstly to fuel the hydraulic motor’s working chamber and energy accumulator. Due to excessive load, the hydraulic motor is under the locked rotor conditions, with the maximum motor’s output torque at this moment. At the moment of firing, the maximum acceleration of the launching system is faster than the motor’s maximum acceleration, and the automatic mechanism’s feeding mechanism’s speed is faster than ammunition feed system’s speed, with the motor being dragged to move. At this moment, the hydraulic power unit and energy accumulator fuel the hydraulic motor quickly, and the motor outputs the torque required for load quickly. During the firing process, when the hydraulic motor’s speed is faster than the automatic mechanism’s speed, the hydraulic motor will drive the ammunition feed system to rotate to reduce the launching system loading resistance, the launching system’s acceleration increases until the launching system’s speed equals to the motor’s speed.

4.2. Selection of key elements

4.2.1. Selection of hydraulic motor

The pressure of the hydraulic motor is calculated as:

\[ P = \frac{2\pi T}{V_m} \]

In which, \( T \) refers to the hydraulic motor’s operation torque;

\( V_m \) refers to the hydraulic motor’s displacement;

As shown in Article 2.2, the hydraulic motor’s operation torque ranges from 200Nm to 400Nm. The working pressure range of the hydraulic motor can be calculated upon determining the hydraulic motor’s displacement.

4.2.2. Selection of energy accumulator

According to Boyle's law \( P_0 V_0^k = P_1 V_1^k - P_2 V_2^k = C \), we can get:

\[ \Delta V = V_1 - V_2 = V_0 \left( \frac{1}{P_1^k} - \frac{1}{P_2^k} \right) \]

\[ P_0 = 0.25P_2 - 0.9P_1 \]

\[ V_0 = \frac{\Delta V (P_1/P_0)^{1/k}}{1 - (P_1/P_0)^{1/k}} \]

In which: \( C \) is a constant;
P₀ refers to the air-filled pressure;
V₀ refers to the air-filled volume, namely, the total volume of the energy accumulator;
P₁ refers to the minimum operating pressure, namely, 3.69MPa;
V₁ refers to the air volume when the pressure is P₁;
P₂ refers to the maximum working force, namely, 7.39MPa;
V₂ refers to the volume when the pressure is P₂;
∇ refers to the effective oil discharge amount;
k refers to polytropic exponent;
Upon determining the working time of the energy accumulator, the initial volume valve of the energy accumulator can be obtained according to the above formula.

5. Conclusion
(1) This new type of gun, by applying the hydraulic system as the auxiliary power, can take advantage of the hydraulic motor’s locked-rotor characteristics and hydraulic system’s rapid response characteristics to achieve better coupling between the ammunition feed system and the launching system.

(2) In this paper, the dynamic simulation model of this new type of automatic gun is established, and the simulation model’s validity has been verified via tests. Based on the simulation model, this paper further studies the influence of constant torque and changing torque output by the hydraulic motor on the system’s dynamic characteristics, and determines the optimum operation torque of the hydraulic motor.

(3) The auxiliary power hydraulic system designed according to the working characteristics of auxiliary power hydraulic system can meet the power demands of ammunition feed system under the conditions without lowering the firing rate.

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