Research on joint simulation technology of fire dynamics and servo control of self-propelled antiaircraft gun during moving

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Abstract. Taking self-propelled anti-aircraft gun as the research object, this paper presents a joint simulation method of shooting dynamics and servo control during the course of self-propelled anti-aircraft gun. Aiming at the matching between structural parameters and servo control parameters of self-propelled anti-aircraft gun, an evaluation and optimization design method is proposed. The platform of the joint simulation system of dynamics and servo control is mainly composed of road-body-turret dynamics model, fire control module, elevation control compensation module, azimuth control compensation module and motor module. The control compensation module realizes the control strategy by PID (Proportional-Integral-Differential) control of position and speed loop. The motor module achieves the system control torque output through the current loop and the motor. These modules constitute the joint simulation design model of dynamics and servo control. By comparing the output of the simulation system with the actual firing test results of self-propelled antiaircraft gun, the effectiveness of the method is verified by the firing line error analysis under different experimental conditions. This method can be used to evaluate the tracking accuracy of the system at the design stage, which is helpful to reduce the development cost and shorten the development period.

1. Introduction

Under the condition of modern war, the self-propelled antiaircraft gun is required to have the ability of marching fire and high shooting accuracy. Therefore, countries all over the world attach great importance to the shooting ability of self-propelled weapon system in marching fire, which requires not only good maneuverability, but also effective attack on enemy targets in the process of moving. In the face of the vast battlefield environment, the changing geographical characteristics, the varying degree of road undulation and the change of vehicle speed will cause the change of dynamic response of vehicle and then the muzzle vibration. In order to carry out high mobility operations, the stability system of the self-propelled antiaircraft gun must have strong adaptability, so as to overcome the interference of the carrier turbulence caused by the uneven road surface on the sight line and firing line.

For the existing self-propelled antiaircraft guns in China, on the rugged road surface, no matter the track type or wheel type, the shooting line of marching fire has a low hit rate to the target due to the decrease of the stability accuracy caused by the change of terrain or the impact of the gun during shooting [1]. Based on the joint simulation technology of fire dynamics and servo control of self-propelled antiaircraft gun during moving, the shooting accuracy of the shooting line stability system of the self-propelled antiaircraft gun can be effectively improved [2], the combat capability of the self-
propelled antiaircraft gun during moving can be improved, so that the technical support for the development of new equipment and the transformation of the existing equipment can be provided. Based on modern design theory and method, modern computer simulation technology will greatly shorten the development time and reduce the design cost. By the establishment of launch dynamics theory and modern control methods, the joint simulation of the system is realized [3], and the advantages of virtual prototype technology are fully utilized to simulate the operation process of the system and find the optimal parameter matching of the system.

In this paper, by constructing the joint simulation model of the dynamics model including the road, vehicle, turret and landing part, and the stability control model of the shooting line, the attitude response of the vehicle body under the joint action of the shooting load, the road excitation load and the control drive is studied, and the disturbance characteristics of the shooting line are predicted, which is a reference for the stability control algorithm of the shooting line and the stability control device of the shooting line. Based on the theoretical analysis of the dynamics of the self-propelled antiaircraft gun, combining with the research of the vehicle body attitude acquisition, control scheme and control structure, the shooting line stability control device is constructed, and the fast compensation algorithm of shooting line stability is designed.

2. Fire dynamic modelling of self-propelled antiaircraft gun during moving
Based on the theory of flexible multi-body system dynamics, vehicle driving dynamics and gun fire dynamics, the transfer process and mechanical modeling method of firing load along the gun body, gun's receiver, cradle, turret, chassis and ground are mainly studied, and the firing dynamic model of self-propelled anti-aircraft gun is established. The system model is shown in figure 1.

![Figure 1. The fire dynamic model of self-propelled anti-aircraft gun.](image)

2.1. Topological analysis of wheeled self-propelled anti-aircraft gun during firing in motion
Taking hinge to describe the connection between components including kinematic pair, contact-impact pair, elastic components, force element, etc., the topological relationship of the whole gun system is shown in figure 2.

(1) The barrel is an elastic body, and the first 80 modal coordinates are taken as the degree of freedom of deformation. The rigid connection is defined between the muzzle brake and the barrel, the barrel and the gun's receiver, and the gun's receiver and the revolving chamber.

(2) The sliding hinge and contact / impact pair are defined between the gun's receiver and the cradle, and the spring element is defined at the position of the recoil spring.

(3) The cradle and turret are connected by trunnion and sector gear to define the rotating pair and contact / impact pair respectively.

(4) The turret is fixedly connected with the upper bezel, the lower bezel is fixedly connected with the vehicle body, and the contact / impact pair is defined between 201 steel balls, the upper bezel and the lower bezel respectively.

(5) Eight wheels are connected to the vehicle body through suspension, and the contact / impact relationship between each wheel and the ground is defined.
Figure 2. The topological relationship of the whole gun system.

In conclusion, the system is divided into 261 rigid bodies and 1 elastomer, 13 sliding hinges, 25 rotating hinges and 17 consolidation hinges. There are 1244 degrees of freedom of motion and 80 degrees of freedom of deformation in the whole gun system, and the constraint relationship of fire components is shown in Table 1.

| Components                        | Constraint relationship       |
|-----------------------------------|-------------------------------|
| muzzle brake, barrel              | consolidation hinge           |
| barrel, revolving chamber         | consolidation hinge           |
| barrel, gun's receiver            | consolidation hinge           |
| gun's receiver, cradle            | sliding hinge                 |
| cradle, turret                    | rotating hinge                |
| cradle gear, elevating pinion     | contact / impact              |
| elevating pinion, turret          | consolidation hinge           |
| Turret, upper race                | consolidation hinge           |
| upper race, lower race            | contact / impact              |
| lower race, vehicle body          | consolidation hinge           |

Via the analysis of the topological relationship of the self-propelled antiaircraft gun, it can be seen that the load that affects the dynamic response of the chassis includes two parts: one is that the firing load is transmitted to the vehicle body through the gun body, gun’s receiver, cradle and turret; the other is that the road spectrum is transmitted to the vehicle body through the wheel and suspension.
Therefore, in order to reveal the law of chassis attitude response frequency during firing in motion, the key to the research is to model the connection between the main components [4].

3. Generation of 3D road roughness data based on MATLAB

Because the pavement roughness has the characteristics of random ergodic states [5], it can also be discretized in the transverse direction of the pavement to obtain the distribution of the longitudinal pavement roughness in each transverse discrete position. If the longitudinal direction of the pavement is x and the transverse direction is y, the roughness of the pavement in the three-dimensional space can be expressed as equation (1):

\[ q(x, y) = \sum_{i=1}^{m} \sqrt{2G_q(n_{mid,i})\Delta n_i \sin(2\pi n_{mid,i}\sqrt{x^2 + y^2})} + \theta(x, y) \]  

(1)

\( \theta(x, y) \) is the random number at any point (x, y) between \([0, 2\pi]\) on the road. Based on this simple formula, the distribution of road roughness in three-dimensional space can be easily obtained. According to the above calculation requirement, the spatial distribution of road roughness under given conditions is calculated via MATLAB.

Taking the D-level and E-level pavement as examples, the paper analyzes the road roughness and generates the three-dimensional terrain data with the length of 150 m and the width of 30 m (the distance interval between the generated data is 0.1 m).

Figure 3 and figure 4 are three-dimensional road roughness curves under different levels.

![Figure 3. road roughness curve under D-level pavement.](image1)

![Figure 4. road roughness curve under E-level pavement.](image2)

4. Joint simulation system

4.1. Working principle of control system

The difficulties in the stability control of self-propelled antiaircraft gun lie in large tracking speed and acceleration, wide range of firing angle, and the center of mass of the rising and falling parts is not in the trunion (disturbance torque caused by vertical vibration), etc. And the poor stability control will cause the gun to move violently, making the firing accuracy worse [6]. In order to solve the above problems, in this scheme, the flat phase method, the phase margin method and the amplitude margin method in the classical control theory are combined to design an effective control algorithm in the position servo controller of the shooting line stabilization device. The system control structure model of the self-propelled antiaircraft gun is designed based on the compensation principle of position loop. Considering the factors affecting the stability of the shooting line and the acquisition of the body attitude of marching fire, the fast compensation algorithm for the stability of the shooting line is constructed.

The compensation is added to the speed loop of the servo control to form the feedforward control, so as to improve the real-time and quick response of the stability of the shooting line. The servo control system is shown in figure 5. The vehicle attitude sensor, velocity loop compensation
decomposing device and servo control component construct the shooting line stability control device together. Via the joint simulation model, the stability effect of firing line under the joint action of road excitation and shooting load is analyzed to verify the effectiveness of the algorithm and the real-time compensation. The azimuth and high and low speed compensation are loaded into the position loop sub module and speed loop sub module of the shooting line stability servo simulation control module built by MATLAB / Simulink respectively. The simulation analysis of shooting line stability is carried out by the servo control algorithm embedded in Simulink. The working principle block diagram of control system is shown in figure 6.

![Figure 5. The structure diagram of the servo control system.](image)

![Figure 6. The working principle block diagram of control system.](image)
4.2. Construction and implementation of joint simulation model

The joint simulation mainly refers to the joint simulation of servo control system and wheeled self-propelled antiaircraft gun on a unified platform to simulate the actual gun firing. The basic principle of the joint simulation is to input the target command and the position information in the dynamic model of the wheeled self-propelled antiaircraft gun as the input information in the bearing system and the height system, and then make the difference. After the position-velocity-current three loop control, the PID control strategy is adopted to make the position information of the dynamic model of the self-propelled antiaircraft gun accurately and quickly track the target command. At the same time, the moment output of the real-time control in the azimuth and height system is taken as the input signal of the firing model of the wheeled self-propelled antiaircraft gun during moving, and the position of the gun is affected by the moment. The system diagram is shown in figure 7.

Among them,
1) Bearing control: is the bearing servo system module, which controls the target command in bearing;
2) Elevation control: is the elevation servo system module, which controls the target command in height;
3) Dynamic model during moving: the firing dynamics module of self-propelled anti-aircraft gun during moving, through receiving the torque in the servo system, acts on the gun orientation and height directions.

The dynamic model is exported as an S-function to a*. M file. Generally speaking, the output of general mechanical system dynamic model is dynamic response, that is, displacement, velocity, acceleration, etc. These responses are also the measured values of sensors in the control system, and the input of the dynamic model of the self-propelled antiaircraft gun is the driving force or torque, which are also the output of the control system. See figure 8 for the joint simulation model of firing dynamics and servo control system during moving.
5. Simulation results

5.1. Joint shooting simulation of grassland road (E-level road) during moving

By comparing the definition of typical pavement and the undulation of grassland road in the national military standard, the simulation of grassland road surface with E-level typical road can be carried out. In order to verify the simulation results, the shooting condition is the same as the measured condition. The shooting line is 90 degrees to the left of the forward direction and the elevation angle is 0. The still self-propelled antiaircraft gun is accelerated at 3.6 km/h, which enters the uniform driving stage at 15 km/h. At the same time, 10 consecutive shots are fired at this stage. After shooting, the self-propelled antiaircraft gun stops at 3.6 km/h acceleration. By comparing fire control data with servo data, the tracking accuracy and tracking effect are analyzed.

5.1.1. Simulation while the azimuth is 0 and the elevation angle is 90°

a) The bearing servo simulation

The input and output of the bearings are shown as figure 9.

![Figure 9. The simulation bearing error.](image)

b) The elevation servo simulation

The input and output of the elevation are shown as figure 10.

![Figure 10. The simulation elevation error.](image)
5.1.2. Simulation while the azimuth is 45° and the elevation angle is 45°

a) The bearing servo simulation
The input and output of the bearings are shown as figure 11.

![Figure 11. The simulation bearing error.](image)

b) The elevation servo simulation
The input and output of the elevation are shown as figure 12.

![Figure 12. The simulation elevation error.](image)

5.2. Simulation results of experimental conditions in a Test Base
Based on the real firing test data in a Test Base as the simulation input, the vehicle body attitude data collected on the bus during the shooting process is imported into the dynamic model. The fire control input of the firing line stability control system is the real firing control input. The control strategy and compensation scheme are investigated by comparing the tracking accuracy of the servo fire control system, and the joint simulation system is verified. The experimental conditions are as follows: the vehicle speed is 15 km/h, the elevation angle is 0°, and the azimuth is 90° laterally. The simulation results are shown in figure 13-16.

![Figure 13. The simulation results of servo azimuth and fire control tracking angle: Blue line represents experimental data while green line represents simulation data.](image)
Figure 14. The simulation results of servo azimuth and fire control error.

Figure 15. The simulation results of servo elevation and fire control tracking angle: Blue line represents experimental data while green line represents simulation data.

Figure 16. The simulation results of servo elevation and fire control error.

5.3. Comparative analysis of simulation and test results

Combined with the typical road model and the Test Base’s test road, a joint simulation model of dynamics and shooting line stability control is established. The disturbance characteristics of the body attitude response to the shooting line stability control system under the joint action of shooting load and road excitation load are studied. According to the system characteristics, the shooting line stability control algorithm and shooting line stability control model are designed and optimized. According to the simulation data of different roads and different shooting angles, the following results can be obtained:

(1) Under the condition of grassland road (E-level road), the maximum error of azimuth tracking is 0.830 mil, the average error is 0.512 mil, and the maximum error of elevation tracking is 3.048 mil when the vehicle is moving at 15 km/h speed, the azimuth is 0 and the elevation angle is 90°; while the azimuth is 45° and the elevation angle is 45°, the maximum error of azimuth tracking is 0.842 mil, the average error is 0.526 mil, and the maximum error of elevation tracking is 3.252 mil, the average error is 1.540 mil.
(2) Under the condition of D-level road, when shooting at the speed of 15 km/h, the azimuth is 0 and the elevation angle is 7.60°, the maximum error of azimuth tracking is 0.830 mil, the maximum error of elevation tracking is 3.121 mil; when the azimuth is 0 and the elevation angle is 33.69°, the maximum error of azimuth tracking is 0.920 mil, the maximum error of elevation tracking is 3.432 mil.

(3) Under the test road condition in the Test Base, the real value of fire control is used as the target input, and the joint simulation model of dynamics and servo control system is used for simulation analysis. The maximum error of azimuth tracking is 0.835 mil, and the maximum error of elevation tracking is 3.271 mil.

(4) By comparing the simulation results of dynamics and servo control with the test results, the simulation results of grassland road are compared with the average value of the test results. At the same time, the two test values are compared with the simulation results respectively. The results with the largest error are: the maximum dynamical tracking error test value is 3.271 mil, the tracking error in the static test firing is 2.550 mil, the corresponding simulation results are 2.816 mil, the accuracy is 86.09% under dynamic condition and 89.57% in static condition, which is in line with the simulation accuracy in the project.

6. Conclusion

In order to better match the dynamic characteristics and servo control system parameters of self-propelled antiaircraft gun, the simulation is carried out on one platform via the joint simulation technology of the firing dynamics and the servo control system in this study. The target command and the current direction and position information of the self-propelled antiaircraft gun are input into the control system through the position-velocity-current loop control. This technology can effectively guide the optimization of control servo system and the improvement of system dynamics.

Based on the multi-body dynamics simulation software and MATLAB / Simulink, the mechanical dynamics model and servo control model of the self-propelled antiaircraft gun are built. From the simulation results, it can be seen that the design of the system is reasonable, the stability is fine, the tracking ability can meet the requirements, the design efficiency is improved, and the development period is shortened.

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