The Continuous High Precision Measurement Technique of Bore Spacing About Rail-Gun

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Abstract. The change of bore spacing directly affects the sliding electrical contact state in the process of electromagnetic launch, so obtaining the data of bore spacing accurately is very important for analyzing the launch process. A continuous high precision measuring device is designed based on the internal gun structure and the characteristics of angular bisector, and the principle and machining error of the whole system are analyzed, and then checked the actual error with the help of high-precision measuring equipment and detection tooling, the results show that the real error is smaller than or equal to 0.5 mm. At the same time, using the device to measure and obtain the bore spacing of a certain caliber rail-gun, and guided the assembly process and assembly process. Practice has proved that the device has ideal engineering application value, and can provide indispensable measurement means for later numerical modeling, assembly process and performance testing.

Keywords: Rail gun · Bore spacing measurement · Angular bisector characteristic · Continuous high precision measurement

1 Introduction

Electromagnetic gun is a new concept weapon that relies on electromagnetic force to launch projectiles at high speed [1]. As a kind of electromagnetic gun, rail-gun uses electromagnetic force to launch projectiles [2]. It has high initial velocity, long range, simple control, and the high cost-effectiveness ratio. At present, the world's military powers have carried out the development of electromagnetic gun weapon systems, which has extremely high potential for military applications in the future [3–5]. The launching process of the rail-gun is essentially a sliding electrical contact process between the armature and the rail under high voltage and large electricity [6, 7]. The rail is the core part of the electromagnetic rail-gun launching assembly, and its processing accuracy and assembly errors directly affect the launch. During the process, the sliding electrical contact state is changed by the fluctuation of the bore spacing. When the contact gap is too large, severe arc ablation occurs at the gap, which has a serious impact on the life of the rail and the attitude of the projectile [8]. At the same time, the random fluctuation of the rail spacing will cause asymmetric wear and collision of the contact surface and other adverse effects, which is extremely detrimental to the launch process and increases the

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risk of disintegration in the bore and rail damage. After consulting related literature, when domestic and foreign researchers deal with the problem of electrical contact between the armature and rail, they regard the contact as the ideal contact state, that is, maintaining sufficient and good contact between the armature and the rail [9]. There are few research reports on the influence of bore spacing changes on the launch process, the main reason is that there is no effective orbital distance high-precision measuring device for the special bore section of the rail-gun. Therefore, carrying out the high-precision measurement of the bore distance of the rail-gun, analyzing the influence of the change of the rail distance on the sliding electrical contact during the launching process, has important guiding significance for the study of rail damage, armature ablation, etc. It is an indispensable analytical method for the simulation modeling of electromagnetic gun weapon systems, life assessment and assembly testing.

2 The Principle of Bore Spacing Measurement

Under ideal conditions, the two rails in the rail-gun maintain a spatial parallel relationship after the assembly is completed. However, in the actual assembly process, due to processing errors, assembly environment and process differences, various errors introduced will cause the bore distance to vary randomly within a certain range along the length. At the same time, during the electromagnetic launch process, the rail is subjected to electromagnetic repulsion. When the rail is assembled, the trail displacement will be restrained in various forms along the length, thereby limiting the range of the rail pitch [10], so the possibility of large deformation of the rail pitch is relatively small. Assuming that the rail spacing changes uniformly within a certain length range, the spatial position relationship between the two rails can be equivalent to two straight lines at a certain angle, as shown the lines C_1D_1 and C_2D_2 in Fig. 1. By taking any point E on its angular bisector AB to make lines EE_1 and EE_2, the lines C_1D_1 and C_2D_2 are perpendicular to points E_1 and E_2, respectively, and connecting points E_1 and E_2. According to the related characteristics of the angular bisector, $\mathrm{E_1E_2}$ and AB perpendicularly intersect at Point $\mathrm{E_3}$, then

$$EE_1 = EE_2 \tag{1-1}$$

Therefore, the trail pitch at point E is the length of the line E_1E_2, and the straight line distance through the measurement line E_1E_2 is the rail pitch at point E.

3 System Measurement Error Analysis

According to the rail spacing measurement principle shown in Fig. 1, build the test system prototype, and theoretically analyze the errors of each part of the prototype. The system error mainly includes two parts, namely the test principle error and the system processing error.

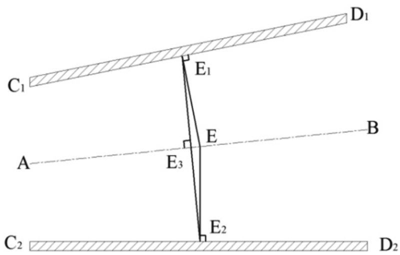


Fig. 1. Principle of track spacing test

3.1 Error Analysis of Measurement Principle

Because the test principle is based on the uniform change of the rail in a certain length range, in practice, there is often a certain degree of bending deformation after the rail assembly, which is the main reason for the principle error of the test method. Assuming that the rail bending deformation within the length range of the measured prototype is shown in Fig. 2, the error introduced by the test principle is S, so

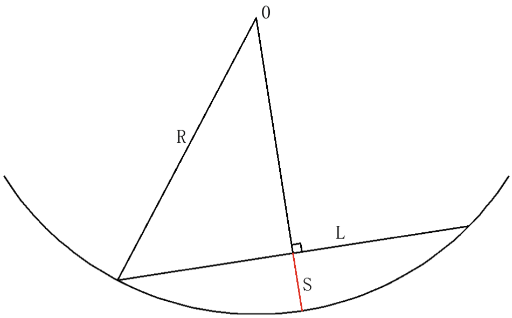


Fig. 2. Schematic diagram of test principle error

$$S = R - \sqrt{\left(R^2 - (L/2)^2\right)} \tag{1-2}$$

In the formula, R is the radius of the curved arc of the rail, and L is the distance of the measuring prototype. It can be seen that the relationship between R and S is linear inversely proportional, that is, to say the larger the R, the smaller the S.

According to the design experience of conventional artillery, the tactical index requirements can be met when the variation range of artillery caliber does not exceed 1% of the caliber. In order to ensure the measurement reliability, sufficient margin is reserved. The measurement principle is applicable to the variation range of rail spacing within 5% of the bore caliber. For a rail-gun with a caliber d and a barrel length l, assuming that the rail is deformed as shown in Fig. 3 after the initial installation, when the bending deformation of the rail is 5% of the caliber d, it can be calculated according to formula (1-3) The bending radius R of the exit rail is:

$$R - \sqrt{R^2 - (l/2)^2} = 0.02d \tag{1-3}$$

$$R = \frac{(0.05 \times d)^2 + l^2/4}{2 \times 0.05 \times d} \tag{1-4}$$

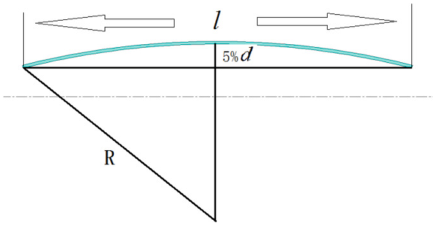


Fig. 3. Schematic diagram of track bending

According to the above analysis, when the rail length and bore diameter are determined, the principle error introduced by this test method is only related to the length of the measuring prototype. Assuming that a rail-gun has a length of 4 m and a caliber of 50 mm, and the measured prototype length $L = 130$ mm, it can be known that when the bending deflection of the entire rail is 5% of the caliber, the principle error introduced by the test method is 1.8 μm.

3.2 Analysis of Errors Introduced by System Machining Precision

The test principle is based on the assumption that the bore spacing changes uniformly within a certain range. The position relationship between the upper and lower rails is regarded as two straight lines forming a certain angle with each other, and the angle bisector is used as the theoretical reference. Therefore, when the processing error causes the deviation of the test standard in the test prototype, it will bring errors to the test system.

As shown in Fig. 4, suppose point O is the connection point between the front support mechanism and the reference plate, the length of the reference plate is recorded as 2 times OE_1, point E is the sensor installation position, that is, the sensor is installed in the middle of the reference plate length, E_1F_1 is the rail spacing theoretical measurement value, and is denoted as d, and the length OE_1 is set to L_1. When the reference plate rotates around point O by angle β due to machining error, that is, when OE_1 rotates to OE_2, the measurement direction E_1F_1 is deflection angle β along with it, and the measured track distance is E_2F_2,marked as d_1.It can be seen that the system test error caused by the processing error is:

$$\Delta\delta = d - d_1 \tag{1-5}$$

As can be seen from Fig. 4:

$$OE_1 = OE_2 = L_1 \tag{1-6}$$

$$E_2G = OE_2 \cdot \sin\beta = L_1 \cdot \sin\beta \tag{1-7}$$

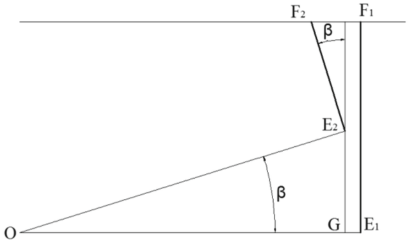


Fig. 4. Measurement error analysis

$$E_2F_2 = \frac{E_1F_1 - E_2G}{\cos\beta} = \frac{E_1F_1 - L_1 \cdot \sin\beta}{\cos\beta} \tag{1-8}$$

$$\Delta\delta = E_1F_1 - E_2F_2 \tag{1-9}$$

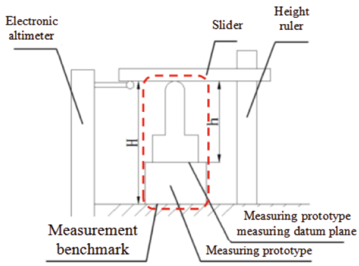
In the formula, d is the bore diameter of a certain gun, β is the deflection angle of the reference plate, when the gap between the mounting holes at both ends of the reference plate is a, and the length of the reference plate is L. It can be seen that the rail pitch test error becomes larger as L and β increase. When the measurement plan is determined, L will remain unchanged. At this time, the error $\Delta\delta$ is mainly affected by $\Delta\delta$ and β is mainly caused by the matching gap between the support mechanism and the reference plate.

In this test plan, $L_1 = 65$ mm, $d = 30$ mm, $L = 130$ mm. When the $H7/h7$ fit tolerance is adopted between the current and rear support mechanism and the reference plate, it can be seen that $\beta = 0.05$, and the size of the error introduced is 11 μm, which can be seen that the error introduced by the measurement principle is less than 1% of the caliber, so the test principle is feasible.

4 Systematic Error Measurement

In order to accurately evaluate the error of the test system, take the whole measuring device as the detection object to verify the system error, the verification principle is shown in Fig. 5. Firstly, the test prototype is placed on a smooth stone measuring plane, and the height ruler is used as the debugging tooling. The slider can slide freely along the height ruler. Taking the measuring benchmark as the reference zero position, it passes through the high-precision electronic altimeter measure the height of the slider from the measurement benchmark, and record it as H_i. At the same time, use the measuring prototype to measure the height of the slider, record it as h_i, and record the initial position height as 0. Compare the two groups of measured slider height data, and the results are shown in Fig. 6.

It can be seen from Fig. 6 that the slider height obtained by the test device basically coincides with the slider height change curve obtained by the electronic altimeter. As the measurement height increases, the two sets of measurement data begin to differ due to the accumulation of errors. The maximum error of the two sets of data is regarded as the total error of the system, and the total error of the system is less than or equal to 0.05 mm.



(a) Measuring principle of distance test data (b) Spacing data measurement process

Fig. 5. Inspection principle and process of track spacing measuring device system

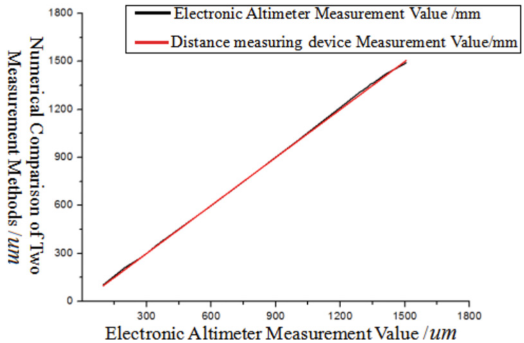
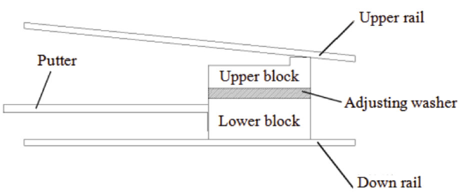


Fig. 6. Comparison of calibration data of track spacing measuring device system

5 Prototype Adaptability Verification

In order to compare the advancement of this rail spacing measuring device and the traditional "plug gauge" rail spacing measuring device, the data measured by the "plug gauge" track spacing measuring device is compared with the measurement results of this test measuring device, as shown in Fig. 7.



(a) Traditional plug gauge (b) measuring principle

Fig. 7. Traditional plug gauge for measuring bore size and its measuring principle

Firstly, use the traditional" plug gauge" to measure the rail spacing at a certain position of the rail, and compare the measured results with the rail spacing measuring device, measured results as shown in Table 1:

Table 1. Comparison of track spacing measurement data

Serial number	Distance from muzzle (m)	Plug gauge measurement result (mm)	Bore spacing measurement results (mm)	Error size (mm)
1	0.8 m	29.2	29.175	−0.025
2	1.6 m	29.8	29.789	−0.011
3	2.4 m	29.1	29.072	−0.028
4	3.5 m	28.9	28.872	−0.028

From the results in Table 1, it can be found that the measurement data using the traditional "plug gauge" method is similar to the rail spacing measurement data, and the difference is small, indicating that the rail spacing measurement device measurement data is accurate and credible. Because the traditional plug gauge is measured by changing the thickness of the adjusting washer, the thickness of the adjusting washer can only be changed by 0.1 mm each time due to the processing accuracy. Therefore, the measurement accuracy of the traditional plug gauge can only be 0.1 mm, and it can only measure partial rail pitch at the point.

6 Engineering Measurement of Bore Spacing

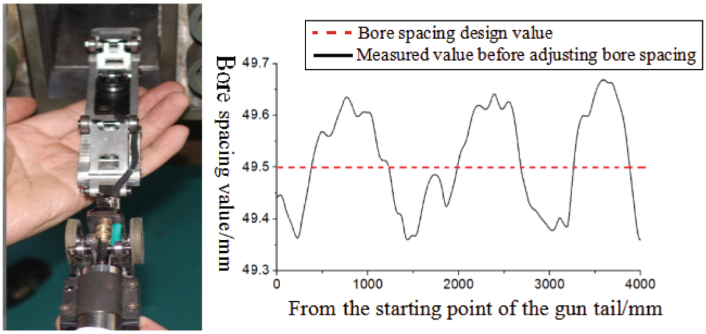
Carry out the measurement of the rail spacing of a screw-fastened rail-gun. The rail spacing was measured along the barrel axis with the tail as a starting point. The acquired rail spacing data and measurement process are shown in Fig. 8.

It can be seen from Fig. 8 that after the initial tightening, the bore spacing changes randomly along the length of the rail, and the change is large. The maximum spacing is 49.68 mm and the minimum spacing is 49.38 mm, which does not meet the rail spacing assembly requirements. Excessive changes in the orbital distance will cause the projectile to collide with the orbit during the launch process, resulting in unstable launching of the armature, and posing safety hazards to the launching process.

In order to meet the assembly requirements, the rail spacing measuring device is placed in the inner bore. By adjusting the rail binding force of each part, and monitoring the change of bore spacing of each part with the preload, the trail spacing in the bore length can be changed evenly. After adjusting the preload of each part, remeasure the track spacing. The results are shown in Fig. 9.

7 Conclusion

According to the special structure of the rail-gun, an innovative orbital distance measurement principle based on the angular bisector characteristics is proposed, and the



(a) Bore spacing measurement process (b) Bore spacing measurement result

Fig. 8. Measured variation curve of rail-gun bore spacing

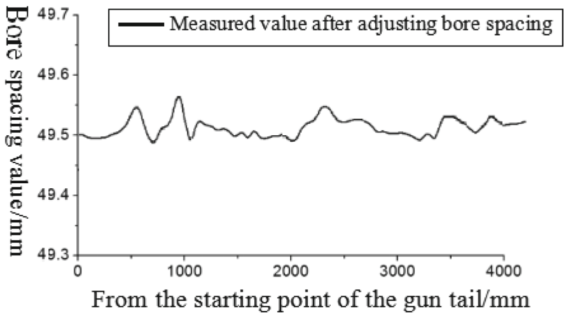


Fig. 9. Measured variation curve of rail-gun spacing after adjusting preload

error size of the measurement system caused by the measurement principle error and the processing accuracy is analyzed. The theoretical analysis result shows that the system error is $\leq$0.05 mm. Then take the entire measurement system as the calibration object, and use the high-precision detection device to verify the accuracy of the entire measurement system. After measurement and testing, the system error of the entire measurement device is less than or equal to 0.05 mm, which can meet the engineering needs.

Through engineering actual measurement of the bore spacing of a certain caliber electromagnetic rail-gun, it is found that the rail spacing varies randomly along the length of the barrel. In order to ensure the assembly accuracy requirements, the bore spacing measuring device is placed in the inner bore to monitor the inner bore distance in real time. By changing various parts The preload force in the borehole can achieve the consistent change requirement of the inner bore spacing, and has achieved good engineering applicability.The proposed continuous high-precision measurement method for rail-gun bore spacing provides a necessary detection method for rail-gun simulation modeling, assembly inspection and performance evaluation, and is of great significance to the development of electromagnetic rail-gun technology.

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