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高精度弹丸质偏心测试系统的设计

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摘要：弹丸质偏心是弹丸性能的重要设计参数。为了提高其测量精度和效率，设计了基于三点法的高精度弹丸质偏心测量系统，介绍了测量原理、计算公式和测量设备，分析了测量误差产生的因素，提出了一种多测试平台和自动调平以及弹体自动旋转90°的设计思想。给出的试验结果表明，质心测量精度≤0.1 mm，偏心测量精度≤0.01 mm，同时满足弹丸高精度质偏心的测量需求。该系统测量范围广、制造成本低，具有广泛的应用开发前景。

关　键　词：弹丸；质偏心；三点法；误差分析
中图分类号：TJ410.6　　**文献标识码：**A

Design of high accuracy inspecting system for measuring centroid and centroidal deviation of bullets

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Abstract: The centroid and centroidal deviation of bullets are important design parameters of bullets. In order to improve the measuring accuracy and efficiency, a high accuracy inspecting system for measuring the centroid and centroidal deviation of bullets based on three point method is designed. The working principle, relevant calculation formulae and the measuring equipment for measuring the centroid and centroidal deviation of bullets are presented, and the main factors affecting measuring precision are discussed. Then, a multiple measuring platform with automatic leveling and column structure autorotation of 90° is put forward. The given experimental results indicate that the measuring precision of the centroid and the centroidal deviation is no more than 0.1 mm and 0.01 mm respectively, which satisfies the qualification needs for high accuracy measuring the centroid and centroidal deviation of bullets. The system has wide measurement ranges, low manufacture costs and broad application and development prospects.

Key words: bullet; centroidal deviation; three point method; error analysis

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1 Introduction

The mass, centroid, centroidal deviation, and other static parameters of bullets are important design parameters. They are related to the aerodynamic characteristics of rockets and missiles, inside and outside ballistic properties, and launch dynamics, etc. These parameters determine the success or failure of the design and the quality for rockets and missiles,and have a great effect on the stability, accuracy of the flight of rockets and missiles. They play a very important role in the ballistic calculation, and have a direct effect on the target hit rate.

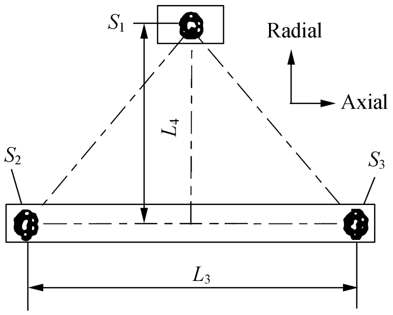
Due to the complex structure of the bullets, a large number of inside components, and uneven distribution of mass, it's difficult to calculate and determine the centroid and centroidal deviation of the bullet accurately based on the general theory (sometimes it's several times or several tens of times of the measured data), so a actual measurement method is important. At present, the measuring methods of the centroid and centroidal deviation of the bullets are mainly a machine relocation method, a multi-point weighing method and a unbalanced moment method[1-5].

From existing measurement modes, the different scale equipment is usually designed according to the mass of the bullet in order to satisfy the measurement accuracy, and a lot of equipment and many steps are often adopted to measure the centroid and centroidal deviation of a bullet, so these bring on low measurement precision and efficiency and waste a great of manpowers, financing and material resources.

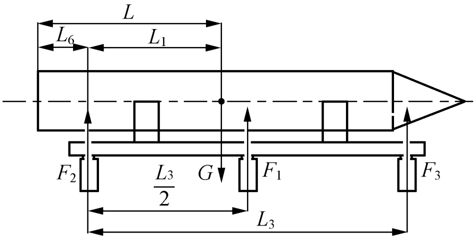
In order to improve measurement accuracy and efficiency of static parameters of the bullets, an automatic high-precision measurement system for the centroid and centroidal deviation of the bullets based on the three-point method is designed. The system uses an industrial computer as the main control unit and a LabWindows/CVI virtual instrument as a development platform, so its structure is simple and designed ingeniously, and the mass of the bullet can be measured, too. Furthermore, by the replacement of the test platform, bullets with different calibers and weights can be measured. Therefore, it has broad prospects for application and development.

2 Design and principles of measurement mechanism

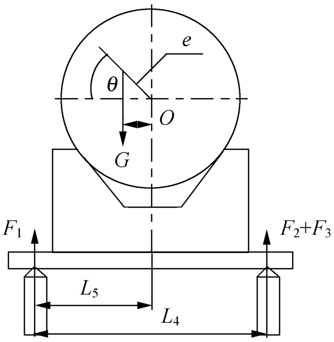
Three high-precision pressure sensors are installed at the bottom of the test platform to compose an isosceles triangle (Fig . 1 (a)) , the



(a) Distribution of sensors



(b)Radial direction



(c)Axial direction

Fig. 1 Principle map of measuring centroid and centroidal deviation bullet to be tested is placed on the V-shaped scaffolds of test platform, which can complete the measurement of the mass, centroid and centroidal deviation.

2.1 Mass G measurement

The mass G_0 of the empty test platform is

$$G_0 = F_1' + F_2' + F_3' \ ,$$

Where F_1', F_2', F_3' are respectively the pressure value on every sensor when test platform is empty.

When bullet is placed in test platform, the mass G of the bullet is

$$G = F_1 + F_2 + F_3 - G_0 \ , \qquad (1)$$

Where F_1, F_2, F_3 are respectively the pressure value on every sensor when the bullet is placed on the test platform. After G_0 is measured at a test, it is an invariable value, so it can be thought as a constant during the test.

2.2 Centroid L measurement

The schematic diagram of measurement principle is shown in Fig. 1 (b).

From the moment equilibrium conditions it can be get:

$$G \times L_1 - F_1 \times \frac{L_3}{2} - F_3 \times L_3 = 0 \ , \qquad (2)$$

Where L_1 is the distance between the centroid of bullet and the weighing sensor 2 in the axial; L_3 is the distance between the weighing sensor 2 and the weighing sensor 3 in the axial (no radial distance); L_6 is the distance between the bullet base and the weighing sensor 2 in the axial.

Then the distance between the centroid of bullet and the bullet bottom $L = L_1 + L_6$,

$$L = \frac{F_3 \times L_3 + F_1 \times \frac{L_3}{2}}{G} + L_6 = \frac{F_3 \times L_3 + F_1 \times \frac{L_3}{2}}{F_1 + F_2 + F_3 - G_0} + L_6 . \qquad (3)$$

2.3 Centroidal deviation e measurement

The schematic diagram of measurement principle is shown in Fig. 1 (c). Before measuring, four generatrixs quartered the bullet circumference are drawn. When measuring, a optional generatrix is used as a start and the bullets are rotated, the pressure value is measured successively by three weighing sensors when the bullets is rotated to 0°、90°、180°and 270°. According to the principle of moment balance:

$$(F_{21} + F_{31}) \times L_4 = G \times (L_5 - \cos\theta \times e) \ ,$$
$$(F_{22} + F_{32}) \times L_4 = G \times (L_5 - \cos(\theta + \pi/2) \times e) \ ,$$
$$(F_{23} + F_{33}) \times L_4 = G \times (L_5 - \cos(\theta + \pi) \times e) \ ,$$
$$(F_{24} + F_{34}) \times L_4 = G \times (L_5 - \cos(\theta + 3\pi/2) \times e) \ .$$

The centroidal deviation e can be obtained by solving the above simultaneous equations:

$$e = \frac{L_4\sqrt{(F_{24} + F_{34} - F_{22} - F_{32})^2 + (F_{23} + F_{33} - F_{21} - F_{31})^2}}{2G} \ , \qquad (4)$$

Where θ is the angle between the horizontal line and the vertical line connecting centroidal deviation with a bullet axis, F_{ij} is the measuring value of weighing sensor i at j time.

3 Analysis of measurement error

3.1 Analysis of the influencing factors of centroid measurement error

Measurement error is derived from a centroid measurement formula(3):

$$\Delta L = \sqrt{\left[\frac{\partial L_1}{\partial F_1}\Delta F_1\right]^2 + \left[\frac{\partial L}{\partial F_2}\Delta F_2\right]^2 + \left[\frac{\partial L}{\partial F_3}\Delta F_3\right]^2 + \left[\frac{\partial L}{\partial L_3}\Delta L_3\right]^2 + \left[\frac{\partial L}{\partial L_6}\Delta L_6\right]^2} \ . \qquad (5)$$

It indicates that measurement error is caused by the mass measurement error, sensor positioning error, the level error of test platform and L_6 measurement error, and the mass measurement error depends on the weighing sensor accuracy, which can be solved by using high precision and good consistency weighing sensor. The accuracy of weighing sensor in this system is 0.01%(its accuracy can be further improved), but the sensor positioning error caused by machining is difficult to determine, which has a worse effect on the centroid measurement precision than the mass measurement error. Therefore, the key to improve centroid measurement precision is to eliminate the sensor positioning error and the level error of the test platform as much as possible.

Then effect of the level error of test platform on the centroid measurement precision is analyzed. Supposed that the angle between test platform and horizontal plane is α, then the centroid calculation formula is:

$$G\times L_1'-\left(F_1\times\frac{L_3}{2}+F_3\times L_3\right)\times\cos\alpha=0\ . \quad (6)$$

Scilicet, if $L_1'=L_1\cos\alpha\leqslant L_1$, then the centroid measurement value will be shorter than an actual value.

For example: if sample is φ122 mm(mass is 21.700 9 kg, centroid L is 118.52 mm), L_3 is 140 mm, L_6 is 40 mm and slope angle α is 3°, then ΔL is 0.162 mm. It exceeds qualification of 0.1 mm.

3.2 Analysis of the effect of generatrix on measurement error

Centroidal deviation measurement value can be obtained by the formula (4) in the three point method, and the measurement error comes from joint influence of the parameter measurement errors in formula (4). Meanwhile, the bullet rotated by 90° each time accurately is the premise of formula (4), otherwise, the error will be brought in centroidal deviation measurement[5].

To make sure the rotary precision of the bullet, the mathod of drawing generatrix is used. The generatrix is drawn manually, as result of the error leads to there is no 90° between the two lines connecting the adjacent generatrixs and axis appears unavoidably, thereupon, the centroidal deviation measurement error can be obtained by

$$\Delta e=\sqrt{\left[\frac{\partial e}{\partial L_4}\Delta L_4\right]^2+\left[\frac{\partial e}{\partial G}\Delta G\right]^2+8\left[\frac{\partial e}{\partial F}\Delta F\right]^2}\ . \quad (7)$$

Then the effect of the generatrix errors on centroidal deviation is analyzed. If there are no generatrix errors, according to the principle of moment balance

$$(F_2+F_3)\times L_4=G\times(L_5+\sin\theta\times e)\ .$$

If there are generatrix errors, we can suppose the rotary angle of the bullet is $90°+\Delta\theta$($\Delta\theta$ is very small: $\cos\Delta\theta\approx1$, $\sin\Delta\theta\approx\Delta\theta$), then:

$$\begin{aligned}(F_2+F_3)\times L_4&=G\times[L_5+\sin(\theta+\Delta\theta)\times e]=\\&G\times(L_5+e\sin\theta\cos\Delta\theta+e\cos\theta\sin\Delta\theta)\approx\\&G\times(L_5+e\sin\theta+e\cos\theta\times\Delta\theta)\ .\end{aligned}$$

Above formula can be simplified as:

$$(F_2+F_3-G\times e\times\cos\theta\times\Delta\theta/L_4)L_4=G(L_5+e\sin\theta)\ , \quad (8)$$

Where the centroidal deviation error is mainly caused by the last part of the left bracket,

$$|G\times e\times\cos\theta\times\Delta\theta/L_4|\leqslant|G\times\Delta\theta\times e/L_4|\ . \quad (9)$$

So supposing $\Delta F=G\times\Delta\theta\times e/L_4$.

For example: if sample is φ 122 mm, $L_4=40$ mm, $\Delta\theta$ is 0.5° and its radial centroid and centroidal deviation $e_{\max}$ is likely the 1/10 diameter of the measured bullet, then $\Delta F=0.057\ 7$ N, and the Δe is 0.01 mm by equation (7), It exceeds the qualification of 0.01 mm.

4 Solving measures

To reduce above errors and improve measurement accuracy, following measures are adopted.

(1) The positioning error of sensor is a systematic error, which can be reduced to the range of 0.03% by a precise design and installation.

(2) Due to the uncertain position, L_6 can only be measured manually, the personal error is big. Then, a grating ruler with a accuracy of 0.01 mm is used to measure the L_6. By adjusting, the measurement error caused by the non-parallelism among of the grating ruler, guide and the axis of the bullet can be reduced to the range of 0.005 mm. The positioning error caused by the repetition to install bullets in the test platform and the support test platform by a weighing sensor can be eliminated through measuring every bullet independently, the measurement accuracy of L_6 can be reduced to the range of 0.05 mm.

(3) Auto-leveling test platform (shown in Fig. 2) is supported by three support shafts (shown in Fig. 3) , each of them is connected with a motor through the framework, coupling and an active gear, a driven gear, a bearing chock, a screw-nut and a bed frame. a motor servo control system is used to drive three support shafts manually or automatically. The motion displacement measured by obliquity sensors is feedback to control a software.

As Figure 3 , when leveling, an electric leveling device is started , which will push the screw-nut and sensors up together and make the test platform and obliquity sensors detach from the bed frame. Then the leveling device with maximum displacement found through the obliquity sensors is turned off. One of the other two leveling devices of axial direction is used to fine control, the result of which is to make the obliquity sensor of axial direction zero output. So leveling of axial direction is realized. Then leveling devices of axial direction is fine driven to make obliquity sensor of radial direction zero output. So leveling of radial direction is realized. The outputs of the three weighing sensors are recorded, and the mass of test platform can be obtained. Then measured bullet will be put on the test platform and repeat this process, then the mass of bullet can be obtained.

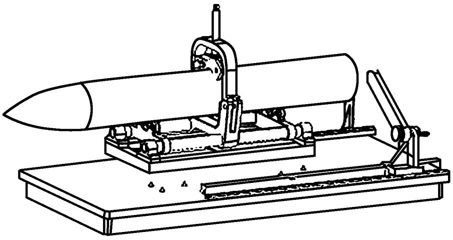


Fig. 2 Mechanical structure of equipment

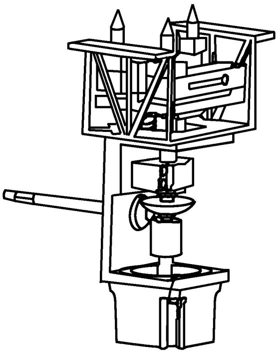


Fig. 3 Structure of automatic regulating level

(4) To realize the precise rotation 90 ° of the bullet, friction drive principle is used to rotate the bullet 90 ° precisely each time. As Fig. 2 shows that it is composed of V-shaped friction wheels, a stepping motor and an encoder, thereinto, friction wheel materials is steel matrix composites, the friction wheels are supported by four rolling bearings and the encoder connected with friction wheels is used to ensure the rotary precision. The steps of the motor determined by the ratio of bullet calibre to friction wheel diameters make sure that the bullet is rotated 90 ° precisely each time, which can reduce personal errors.

5 Measurement equipment and experimental results

The measured bullets have many types and wide ranges, and the measurement precision are prescribed in GJB2235-94 with measuring precision in the mass of 0.04% F. S(full scale), the centroid more than 0.1 mm and the centroidal deviation more than 0.01 mm. Therefore, all measured bullets are divided into four typical intervals according to their mass and lengths. The different test platforms use different high precision weighing sensors. The bullets belonging to a same interval use a same test platform. All these test platforms share one bed frame. By replacing different test platforms on the same bed frame, the bullets with different calibres can be measured and their high measurement precision can be ensured. Mechanical part of the equipment is shown in Fig. 2.

There isn't a direct metrology method for the equipment in our country now and several kind of indirect methods were used to calibrate the equipment in this system. The mass and geometric sizes of the standard sample are measured out, then the theoretical values of the centroid and centroidal deviation are calculated by theoretical formula. Finally, the measurement value of mass, the theoretical values of the centroid and centroidal deviation are used to calibrate the equipment. According to this method, the measurement value is compared with the theoretical value, which can obtain the precision of the measured instrument. The measurement value and theoretical value are shown in Table 1 and Table 2:

Tab. 1 measured results of the centroid of samples

Test platform	Mass (kg)	Theoretical value of centroid(mm)	Measurement value of centroid (mm)	Centroid error (mm)
1	2.757 2	69.025	68.986	0.039
	1.748 7	39.49	39.502	0.012
2	24.088 7	400.05	400.042	0.037
	24.088 9	400.05	400.071	0.066
3	15.572 7	126.51	126.468	0.042
	4.440 6	75.225	75.275	0.050
4	44.543 1	244.175	244.187	0.012
	33.677 8	162.03	161. 985	0.045

Tab. 2 Measured results of the centroidal deviation of samples

Test platform	Mass (kg)	Theoretical value of centroidal deviation (mm)	Measurement value of centroidal deviation (mm)	centroidal deviation error (mm)
1	2.209 5	0	0.006	0.006
	2.757	0	0.004	0.004
2	11.998 3	0	0.003	0.003
	11.979 6	0	0.006	0.006
3	9.594 1	0	0.009	0.009
	9.5935	0	0.004	0.004
4	46.533 3	0	0.003	0.003
4	6.533 2	0	0.005	0.005

The above experimental results have shown that the measurement values of the centroid and centroidal deviation for all test platforms satisfy the qualification, the measuring precision of the centroid is no more than 0.1 mm and the measuring precision of the centroidal deviation is no more than 0.01 mm.

The equipment has been widely used in the tests of ammunition at present. The large numbers of tests indicate that the equipment proves good effect in practical use, which plays extremely role in the tests of ammunition.

6 Conclusions

Through above measurement method introduction, formula derivation, error analysis and measures of reducing error, it shows that the test equipment has many merits and broad prospects for application and development.

(1) All test platform shared one bed frame, which can ensure measurement accuracy of the bullets with different calibres. Meanwhile, the utilization rate of the equipment has significantly improved, and the cost of equipment is greatly reduced.

(2) Manual leveling method is replaced by auto-leveling method, which greatly enhances the accuracy of leveling, alleviates the workloads and improves efficiency.

(3) Automatic accurate way to rotate 90 ° replaces the generatrix method, which greatly reduces the error.

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●下期预告

可筛选乳胶微粒的介电泳微马达陷阱：从分立单元到片上实验室

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提出一种可分析、筛选乳胶微粒的介电泳陷阱与微马达，并以此为核心单元讨论了片上实验室的组建。设计了可集中样本预处理、分离筛选与微马达驱动等多个功能于一体的微分析芯片，并优化了各分立单元的作用效果。用新的螺旋-叉指和螺旋-城堡电极代替了传统的螺旋状或者叉指、城堡状电极，可以分开大小不同的乳胶微粒，而不必借助电渗流的作用，分离效率达 90%以上。发现当激励信号为驻波时，样本分离电压比普遍使用的行波信号降低 50%。对于起介电泳筛选作用的城堡状电极进行了侧向和轴向的非均匀化处理，提高了对微粒尺寸的敏感性，可以从混合液中分离 70%的小微粒。有限元分析和实验结果表明，与参考文献中提到的芯片结构相比，电极的新排布方式增加了轴向场强梯度，分离电压比传统方法降低了 80%。