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Testing method of explosive function based on motion energy balance

Xin Zhang, *Chundong* Xu*, *Yucheng* Shi, and *Xuehui* Zhang
College of Mechanical Engineering, Nanjing University, Jiangsu 210094, China

Abstract. The functional capacity of explosives is an important indicator for evaluating the explosive power of explosives. Based on the motion energy balance and the principle of artillery launching, this paper designs a functional capacity evaluation device for explosives. Based on the analysis of the device, an evaluation model for the functional capacity of explosives is established. The measurement parameters is determined according to the model; a comprehensive testing system for functional capacity was constructed, and the feasibility of the functional capacity testing device was verified through testing. The results show that the test method can quantitatively measure the functional capacity of explosives, and can effectively measure and evaluate the explosive performance of explosives.

Keywords: Explosive, Work, Movement energy, Test Methods.

1 Introduction

The functional power of an explosive refers to the work done by the high-temperature and high-pressure detonation product generated when the explosive explodes to expand and compress the surrounding medium, deforming, destroying, and scattering the medium. It is also called the explosive power of the explosive and is one of its components. Important performance indicators are vital to the optimal design of explosive components and the rational application of explosives and cannot be directly measured [1]. The current methods for measuring the functional power of explosives mainly include lead casting method, ballistic mortar method, blasting funnel method, ballistic throwing method, and underwater explosion method, converting the work done by explosives into plastic deformation energy of external substances, including kinetic energy and bubble energy [2].

The lead casting method judges its functional capacity through the expansion volume of the lead hole in the lead casting before and after the explosion. Although this method is simple to operate, the lead casting manufacturing process is strict, the cost is high, and the ballistics of the same period cannot be reused after a single test. The mortar gun [3] puts explosives into the cavity of the mortar and converts the work of the explosion into the energy of the mortar's reverse swing and the kinetic energy of the shell. This method is simple to operate and low in cost, but its function conversion ratio not very well. The blasting funnel method judges the functional capacity on the basis of the ratio of the radius to the depth of the funnel pit generated after the explosive is exploded. This method has a simple

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* Corresponding author: chundongxu@126.com

measurement process, a large amount of charge in a single measurement, and is adaptable to the environment. Although it has good performance, low cost, and convenient for engineering applications, the test results have poor reproducibility [5].The ballistic [6] throwing method measures the functional power of the explosive by measuring the distance that the steel cover is thrown after the explosive explodes and solves the problem of poor reproducibility. The measurement device has a simple structure, and the measurement results are more accurate. It is a relatively common method used for functional power testing. However, the site space requirements are relatively high, the steel cover is of large quality, and the transfer and transportation of the device are difficult because the ballistic projectile distance is approximately 40 m. The underwater explosion method [8] is unstandardized. Liu and others measured the explosive power of industrial explosives by building a tank with an upper mouth diameter of 45 m, a bottom diameter of 12 m, and a depth of 9 m. Although the measurement results are accurate, the cost is high, and the site space is large, making this method unconducive to project promotion.

This paper compares the process of artillery firing ammunition on the basis of motion energy balance theory and designs a method to quantitatively test the functional power of explosives. The functional energy of the explosive is converted into the kinetic energy of the piston slide, the hydraulic energy of the retractor connected to it, and the friction resistance to calculate the functional power of the explosive. This process is performed through the high-temperature and high-pressure gas generated by the explosive explosion to push the piston rod to do work. The functional capacity of explosives is converted into parameters that can be directly measured for calculation and analysis. LabVIEW software is used to process the experimental test data for obtaining the explosive power and evaluating and analyzing the functional power of explosives.

2 Design of functional power device with explosives

2.1 Model composition

As is shown in Figure 1, the functional capacity of explosives is converted into other forms of energy for measurement. A functional force test machine is designed for explosives on the basis on artillery transmitters, and its structure is similar to the structure and principle of ordinary artillery. The propellant in the artillery is replaced with the explosive that needs to be tested, the shell with a piston slide that matches the barrel is replaced, and a pair of recoiler and retreat at one end of the piston rod are arranged, constituting the function of the explosive.

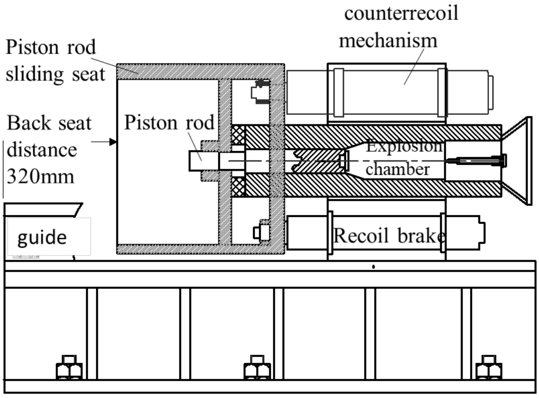


Fig. 1. Sketch of the working method.

The device is mainly composed of explosive tube, piston rod, retractor, guide rail, detonating tube, and other components. In the experiment, the explosives bag is placed in a special cartridge, an electric primer is installed at the bottom of the cartridge, and a detonating tube is inserted through the screw-type latch for easy detonation. The connected explosion tube and piston rod can be displaced by the air pressure inside the explosion chamber. The piston and the explosion tube are each equipped with a hydraulic retraction machine to reduce the displacement, and a recuperator is used to restore the position of the device. The entire device is placed on the guide rail and is used to fix the movement direction of the piston and explosive tube.

2.2 Working principle

After the explosive is detonated by the detonating tube, an explosion shock wave is generated, and the gas in the explosion chamber instantly expands. The resulting shock wave pushes the piston and the explosion tube to move along the guide rails of the frame to two sides, driving the connected hydraulic parking machine to move with them. During this process, the explosive tube has been in a closed state, and the thermodynamic equation (1) can be established.

$$P_0 V_0^{\,n} = P_A(t) \cdot \{V_0 + S_A \cdot [x_1(t) + x_2(t)]\}^n \tag{1}$$

In this formula, P_0 is the final stable pressure value after the explosion; V_0 is the initial volume of detonation; n is the variability index with a value between 1.0 and 1.4; $P_A(t)$ is the pressure value in the explosion cavity at time t ; S_A is the force-receiving area of the piston rod; $x_1(t)$ and $x_2(t)$ are the displacement of the explosive tube and the piston rod at time t, respectively.

It can be seen from the formula that as the displacement increases, the inner volume V of the explosion chamber becomes larger, and the gas pressure $P_A(t)$ gradually decreases. The blast tube and the piston slide drive the connected hydraulic parking machine and also produce displacement along with their displacement. Displacement and friction f occur, and the retraction machine $F_{\phi 1}(t)$ and $F_{\phi 2}(t)$ starts to consume energy. At this time, the gas pressure is greater than the resistance, and the piston accelerates. The force diagram is as follows.

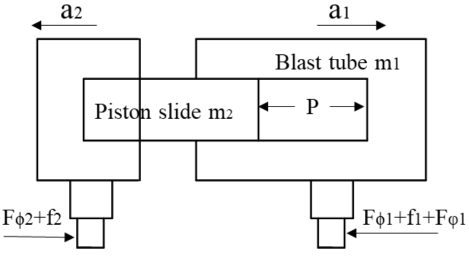


Fig. 2. Force diagram.

The gas volume gradually increases, and the pressure begins to decrease due to the movement of the piston. When the gas pressure is less than the resistance, the piston starts to decelerate until the speed reaches zero. When the air pressure returns to atmospheric pressure, the re-entry machine returns the device to its position, and the work ends. The following differential equations of motion can be established.

$$m_1 a_1 = m_1 \frac{d^2 x_1(t)}{dt^2} = P_A(t) \cdot S_A - F_{\phi 1}(t) - F_{\varphi 1}(t) - f_1 \cdot \tag{2}$$

$$m_2 a_2 = m_2 \frac{d^2 x_2\left(t\right)}{dt^2} = P_B\left(t\right)\cdot S_B - F_{\phi 2}\left(t\right) - f_2 \cdot \qquad (3)$$

The explosive energy of the explosive *E*.

$$E = P_A\left(t\right)\cdot S_A \cdot x_1(t) + P_B\left(t\right)\cdot S_B \cdot x_2(t) \qquad (4)$$

In this process, the movement of objects that consume explosives as functional energy includes the kinetic energy generated by the movement of the explosive tube and the piston, the work of the internal hydraulic resistance of the retraction machine, the work of the internal gas resistance before the resetting of the re-entry machine, the movement of the device on the guide rail, and the work of friction resistance.

$$E = \frac{1}{2} m_1 v_1^{\,2} + \frac{1}{2} m_2 v_2^{\,2} + F_{\phi 1}\left(t\right) x_1(t) + F_{\phi 2}\left(t\right) x_2(t) + F_{\varphi 1}\left(t\right) x_1(t) + f_1 x_1(t) + f_2 x_2(t) \qquad (5)$$

3 Functional evaluation model of explosives

In accordance with the analysis of the working principle in the previous section, the functional energy conversion block diagram of the explosive can be obtained, as shown in Figure 3.

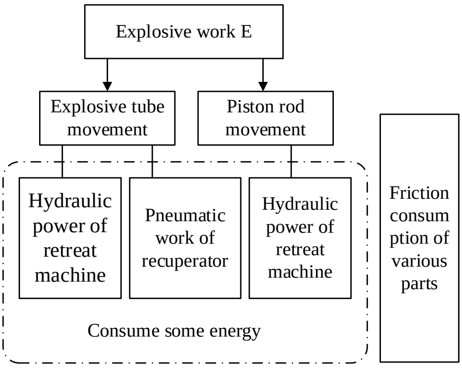


Fig. 3. Block diagram of functional energy conversion for explosives.

If the explosive energy *E* of the explosive is required, the following conditions must be known.

- The total mass of the explosive tube and its slider is M_1, the maximum speed is V_1, and the maximum kinetic energy of the explosive tube and its slider moving backward is $E_1=0.5M_1V_1^2$;
- The total mass of the piston and its sliding seat is M_2, the maximum speed is V_2, and the maximum kinetic energy of the piston and its sliding seat is $E_2 =0.5M_2V_2^2$;
- The hydraulic resistance generated during the recoil of the explosive tube parking machine is P_1, and the recoil length is L_1. Thus, the hydraulic energy consumption is the curve P_1–L_1 area $E_3=F_{\phi 1}(\mathrm{t})\, x_1(t)$.
- The air pressure resistance generated during the recoil of the explosive tube recoil machine is P_2, and the recoil length is L_1. Thus, the air pressure energy consumption is the curve P_2–L_1 area $E_4=F_{\psi 1}(\mathrm{t})\, x_1(t)$.
- When the piston moves forward, the hydraulic resistance generated by the retractor is P_3, and the recoil length is L_2. Thus, the hydraulic energy consumption is the curve P_3–L_2 area $E_5=F_{\phi 2}(\mathrm{t})\, x_2(t)$.

- The frictional resistance work of the moving parts of the system includes the friction between the blast tube slider and the frame slider. Set the friction coefficient as *f*, and we have

$$E_6=f * (M_1gL_1+ M_2gL_2).$$

Thus, the functional capacity of the explosives is expressed as

$$E= E_1+E_2+E_3+ E_4+ E_5+E_6. \qquad (6)$$

4 Design of functional test system

From the analysis in the previous section, the following parameters need to be measured. 1) The displacement and maximum speed of the piston rod and explosive tube; 2) The relationship between the air pressure in the re-entry machine and the displacement; 3) The relationship between the hydraulic pressure in the retraction machine and the displacement; 4) The relationship of the displacement of the recoil device with time; 5) The frictional resistance of the device's movement.

A test system for explosives as a functional energy test device is designed, which is composed of sensors, signal conditioners, signal cables, and data acquisition instruments, to measure these parameters. The test sensors mainly include pressure sensors, displacement sensors, and acceleration sensors.

4.1 Sensor selection and installation

(1) Displacement sensor

The displacement sensor is used to measure the movement displacement of the explosive tube and the piston and calculate the energy consumed by the retractor/retractor on the basis of the pressure in the retractor/retractor. A sensor with high measurement accuracy is required because the explosion process is extremely rapid. Inductive displacement sensors have multiple advantages, such as wide linear range, high test accuracy, and low working environment. At present, the nonlinear index of domestic high-precision sensors has reached 0.1%, which can meet most of the needs. Therefore, linear displacement sensors are actually used. One end is connected to the tested body, and one end is connected to the fixed reference device. The explosion tube can be connected to the piston and the explosion tube because its position is fixed during the actual test. The connection interface with the drawstring is reserved on the piston and the explosion tube. The sensor body and the base are firmly installed.

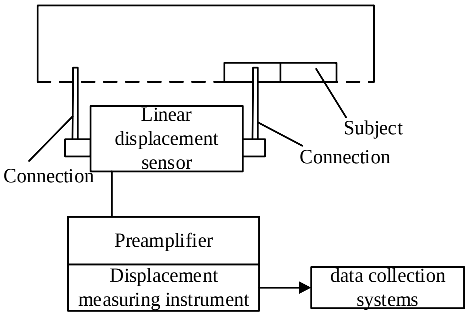


Fig. 4. Schematic of displacement test.

Fig. 5. Displacement sensor installation.

(2) Acceleration sensor

The acceleration sensor is used to measure the acceleration of the movement of the piston and explosive tube. Acceleration sensors can be divided into capacitive, piezoelectric, and piezoresistive types in accordance with their principles. Among them, capacitive acceleration sensors have high accuracy, zero-frequency response, and small temperature drift, and can be used to measure signals with low acceleration and low frequency. The measurement uses a capacitive acceleration sensor that is connected to the piston and the explosive tube separately by means of glue.

Fig. 6. Acceleration sensor installation.

(3) Pressure sensor

The pressure sensor is used to measure the change in the pressure inside the retraction machine and the re-entry machine over time. Considering that the pressure value to be measured in the device is small and the change is relatively stable, a strain-type pressure sensor is selected for measurement.

4.2 Data collection

The model involves the measurement of multiple physical parameters and uses multiple types of sensors. An external DH8302 data acquisition instrument is used to perform multichannel data acquisition on the device. The entire data acquisition includes acquisition parameter setting software and data analysis software.

The acquisition parameter software uses the DHDAS dynamic signal acquisition and analysis system to prepare for acquisition. The data analysis software written in LabVIEW environment can automatically analyze the collected data and give the calculated value of each test quantity.

Figure 7 shows the interface of the designed evaluation software.

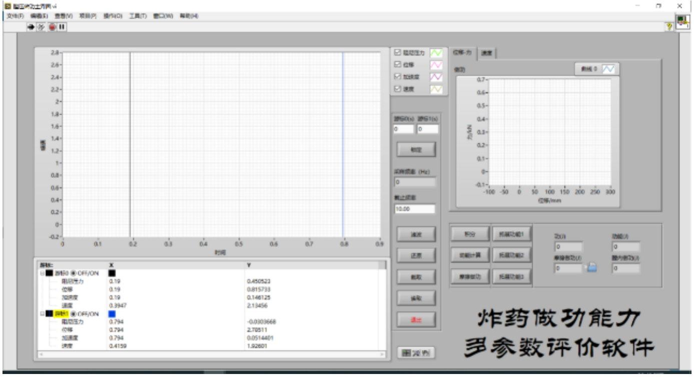


Fig. 7. Multiparameter evaluation software interface for the function of explosives.

Its internal algorithm is mainly composed of three parts: 1) The kinetic energy of the piston. The kinetic energy is obtained by measuring the movement speed *v*1 of the piston. The mass is the mass of all moving parts connected with the piston *m*, $E_1=1/2mv_1^{2,}$ where *m* is the overall mass of the device, which is obtained through actual weighing; v_1 is the movement speed of the device driven by the explosion, which is currently obtained by the acceleration integral measured by the acceleration sensor fixed on the device. 2) The work done by the resistance of the retractor, and the retractor is calculated as Equation (2).

$$E_2 = W_p = \int_0^{x_f} F_p dx\, x. \tag{7}$$

where *FP* is measured by a ring force sensor sheathed at the end of the piston, and *x* is measured by a pull-wire displacement sensor following the displacement of the device. The time synchronization error of each channel of the data acquisition can reach ns level. The force and displacement are measured at the same time. Under the same sampling rate, the sampling length is *N*, the *FP* discrete digital signal at different times [*t*1,*t*2,…,*tN*] is [*F*1,*F*2,…,*F*N] , and the discrete digital signal of *x* is [*x*1,*x*2,…,*xN*]. This condition is used as a sample to construct the time-domain waveform of the *x*-*FP* discrete digital signal. The step length of the dependent variable *x* is a variable and determined by the actual data collected. The trapezoidal rule commonly used in numerical integration is used to calculate the resistance of the retractor to perform work. The force at any time *ti* is recorded as *FPi* and the displacement as *xi*. The calculation method for work is expressed as Equation (3).

$$E_2 = W_p = \sum_{i=1}^{N-1} (F_{p_i} + F_{p_{i+1}}) \cdot (x_{i+1} - x_i) / 2\,. \tag{8}$$

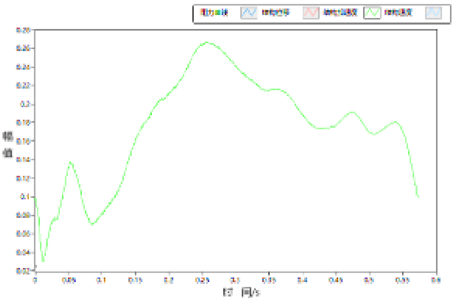
The kinetic energy is obtained by measuring the moving speed *v*2 of the explosive tube, and the mass is the mass *m*2 of all moving parts, except the base and the parking rod of the lower parking machine.

3) The resistance of the device does work. The friction coefficients of the guide rails of the device are assumed to be the same, and the resistance is a certain value. The fixed value is obtained by the force sensor to push the device to move at a constant speed (slow speed), which is the dynamic friction force.

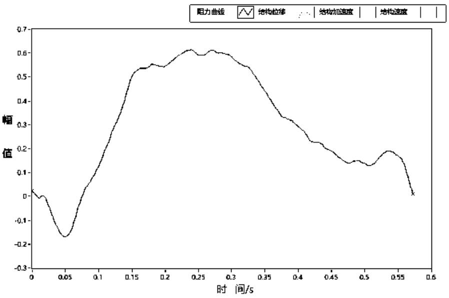
5 Experimental test

Before the experiment, the device is pushed to move at a constant speed (slowly) through the force sensor, and the dynamic friction force is measured for resistance calibration. When the device moves smoothly, it is only affected by the thrust and friction in the horizontal direction. The smooth data after the screenshot are processed and averaged. The friction force obtained is approximately 1.46 KN.

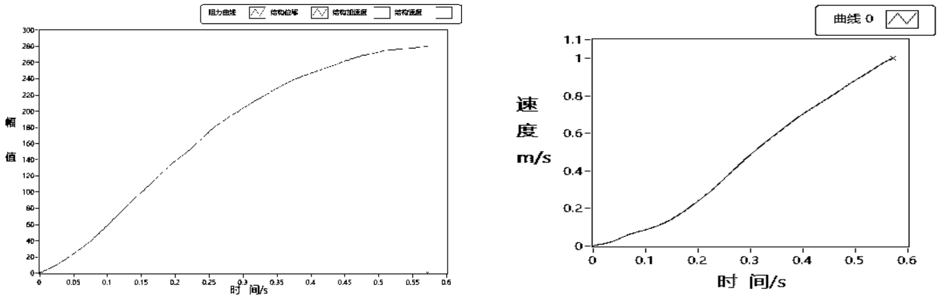
The device is calibrated with 10 g TNT explosive, the JH-14 explosive is sampled, and six experiments are conducted. Figure 8 shows one of the measured data. Only the positive process and screenshots of the data with a time of 0–0.6 seconds are shown to make a clear comparison and analysis, and the remaining negative processes are used for the final calculation of the work results.



a. Acceleration



b. resistance



c. Displacement

d. speed

Fig. 8. JH-14 explosive test measurement data graph.

The parameters change rapidly at this time, and the acceleration first continuously increases, increases to the highest value at 0.25 s, and then begins to decrease. Specifically, the speed increase rate becomes slower when the work done by the retractor and the frictional resistance is greater than the gas pressure. The acceleration decreases to a negative value, and the displacement increases continuously. The displacement increases rapidly at first, decreases, and stabilizes near a certain value. The resistance includes frictional resistance and hydraulic resistance of the retractor. Its value is fixed after calculation. Therefore, the hydraulic resistance can be obtained by subtracting the friction resistance value from the measured data. The trend of the hydraulic resistance and the acceleration fluctuation curve are roughly the same. The speed rapidly increases in 0–0.6 s reaches the maximum when the acceleration is 0, and gradually decreases to zero.

6 Conclusion

The measured data are imported to LabVIEW for automatic calculation to obtain the result, and the data of several measurements are compared by averaging.

This experiment measures only tens of grams, and underwater explosions, ballistic throws, blasting funnels, and other methods measure around a few hundred grams. The lead casting method has a fixed amount of 10 g and is a qualitative analysis of explosive work. Therefore, this article does not make a horizontal comparison with other methods and only compares with the theoretical calculation value in chemistry. The theoretical value is calculated in accordance with the theoretical expression method derived from explosive theory and the first law of thermodynamics. On this basis, Table 1 can be derived.

Table 1. Data result

Explosive	Dosage (g)	ρ/(g.cm^3)	Theoretical η_1/%	Actual η_2/%	Theoretical E_1/kJ	Actual E_2/kJ
TNT	10	1.5	83.3	52.7	35.28	22.34
TNT	20	1.5	83.3	42.5	70.56	48.11
JH-14	10	1.6	86.6	41.2	47.1	29.89
JH-14	20	1.6	86.6	34.5	94.2	50.13

As shown in Table 1, a large gap is found between the actual work value and the theoretical work value, and the higher the theoretical work value of the explosive, the lower the actual work efficiency. Combining the experiment and calculation process, the reasons may be as follows:

- Theoretical error: The theoretical calculation assumes that the experiment returns to standard atmospheric pressure. However, the actual final chamber pressure may not return to atmospheric pressure because the thermal energy and quasi-static pressure of the explosion chamber are not measured. In the experiment, the hydraulic damping of the retreat machine does work, but the damping is ignored in the actual calculation. The mass of some moving components is inaccurately calculated because the explosion tube is fixed on one side.

- Test method: In actual operation and calculation, the grain is uniform by default, its mass and volume are inaccurately measured, the density of the medicine is not determined, and the shock wave test of the same batch of medicine is not conducted to determine the specific drug quantity.
- Sensor selection: The sampling frequency of the test instrument is set at 1 MB. If the frequency is extremely low, the peak value may be missed.
- Experimental device: The theoretically calculated mass of the moving component is small due to the simplified design of the device and the fixed explosive tube. The piston rod is designed with a limit for safety, resulting in part of the work value not being calculated. The piston rod counterweight is enlarged, the length of the guide rail is increased, and a temperature sensor is installed in the bore to monitor the final temperature of the explosion in the bore, which may improve the test accuracy.

The functional evaluation of explosives involves device design, sensor selection and testing, data transmission and calculation. The device is inspired by the artillery launching ballistic process, adding the retreating machine and the recoil machine as consumable parts, and simplifying it to a single-degree-of-freedom system for analysis. The device has the following advantages: 1) Strong adaptability: the lead method and the blasting funnel method are greatly affected by the environment and the filling material, resulting in poor reproducibility; 2) High cost performance: the underwater explosion method requires the construction of a huge pool and cannot be transported. The ballistic throwing method requires an open field, and the steel cover and the base of the device are heavy and not easy to transport. Therefore, this method is more conducive to popularization and standardization. However, this method has some limitations. A certain error is found between the measurement result of the device and the actual energy value, and some parameters , such as vibration damping and residual heat in the bore, are ignored. Although the test method is changed, the overall performance is superior, easy to popularize, and can be used to calculate the functional power of explosives quantitatively. However, it needs to be improved and further tested and practiced to achieve better results. This method can be used as a new test method in evaluating the functional capability of gunpowder.

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