Research on the Measurement of Muzzle Shock Wave Pressure Field for a Naval Gun

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Abstract: The shock wave test of naval gun is of great significance to the safety of the appraisers and the impact on other equipment and parts around the muzzle. In order to test the size and distribution of the muzzle shock wave of a naval gun, a set of shock wave testing system is built, and the test of ammunition under high or low temperature is carried out. On this basis, three interpolation methods of equal pressure surface are analyzed. Finally, we adopt the B-spline method to draw the isobaric field surface and isobaric curve of muzzle shock wave. The results show that the maximum pressure appears at 1 m behind the muzzle, and then the shock wave pressure decreases rapidly, and the attenuation velocity of the shock wave behind the muzzle is significantly greater than that in front of the muzzle; The isobaric line density near the muzzle is higher than that in other areas, conforming to the distribution characteristics of shock wave, and verifying the correctness of the test method; When launching ammunition with high temperature, the density of isobars near the muzzle is much higher than that of low temperature ammunition. The distribution of isobars can provide reference for evaluating the impact of shock wave on other equipment and parts around the muzzle.

1. Introduction

When a naval gun launches a shell, the explosion of its large equivalent warhead can produce a devastating blow to the enemy. The warhead explosion spreads around in the form of squeezing the medium, which carries the characteristics of high temperature, high pressure and high speed, and then forms a shock wave in the medium with explosion as the center. Shock wave is an important way for large equivalent warhead to attack personnel, and destroy equipment and protective facilities. Therefore, shock wave test plays a key role in evaluating the damage power of naval gun, the safety of personnel, the anti-acoustic detection of equipment, and the impact of shock on other equipment and parts around the muzzle[1-2]. Liu Ding of North University of China has designed a distributed shock wave over-pressure test system based on broken line triggering from the perspective of test safety, and compared the measured results with the theoretical results to verify the feasibility of the test system[3]; Wang Xiangqi of National University of Defense Technology has designed a set of shock wave pressure field dynamic parameter test system targeted for such characteristics of the shock wave signal as instantaneous and fast changing[4]; Lai Fuwen, from North University of China, has pointed out that the existing military standard test method of muzzle shock wave isobaric field stipulated is not suitable for the test of muzzle shock wave pressure field of a certain naval gun. He proposed a test scheme of laying sensors in polar coordinates, tested the over-pressure value of shock wave at each point, and obtained the distribution of muzzle shock wave isobaric field of the naval gun[5]; Li Fei of National University of Defense Technology has conducted interpolation research on pressure surface of muzzle
shock wave field based on muzzle shock wave field test, and confirmed the superiority of B-spline curve from algorithm [6]. It can be seen from the above researches that many scholars have conducted in-depth studies on shock wave testing technology and data post-processing algorithm. Meanwhile, the national military standard 2971-97 Test method safety and the serviceability of gun also provides clear guidance for the pressure field test of muzzle shock wave [7], but for a certain type of naval gun, the shock wave test work also needs to be combined with its specific application scenarios. In this paper, according to the requirements of a naval gun muzzle shock wave test, a relevant test scheme based on rectangular matrix is built, and the muzzle shock wave data are obtained when two kinds of shells under high and low temperature are launched. The B-spline method is used to complete the drawing of pressure field surface and isobaric field curve of the two shells, and the distribution of muzzle shock wave is obtained. It serves as an important reference for comparing the distribution difference of shock wave under the two conditions and evaluating the impact of shock wave on other equipment and parts around the muzzle.

2. Construction of shock wave test system

2.1. Characteristics of shock wave signal
When the naval gun shoots, because the unburned gunpowder gas in the chamber is thrown into the air rapidly and burned violently in the air, the adjacent undisturbed air surface will be heated and compressed rapidly, then the shock wave of naval gun is formed. The shock wave produced by explosive explosion or weapon shooting will bring different degrees of damage to military equipment and personnel. The muzzle shock wave pressure field test means to arrange a certain shape sensor array in the area with the strongest shock wave distribution when the weapon shoots, and obtain the shock wave over-pressure value at the corresponding position. On the basis of these test data, the corresponding data processing method is adopted to obtain the distribution of shock wave pressure field (isobaric curve) in the sensor distribution area. It plays a key part in evaluating the safety of weapons. In addition, according to the mechanism analysis of shock wave formation and propagation, the pressure distribution on both sides of the muzzle is symmetrical in the shooting direction, and the pressure center moves with the ray, so the contour density distribution near the muzzle is higher than that far away from the muzzle.

2.2. The composition of test system
Muzzle shock wave test system is a set of multi-point pressure test system. The number of test points is not only lined to the cost of the system, but also directly affects the accuracy of the subsequent isobaric field curve. Therefore, the layout of sensor array should be reasonable in the shock wave test. According to the requirements of the National military standard 2971-97 Test method safety and the serviceability of gun, the distance between the sensors is set to 1 meter in this test, and considering that the shock wave is symmetrical in the shooting direction, only 40 (4×10) sensors need to be placed on one side of the muzzle. In this way, we can cut the cost of the test system. The specific layout of the sensors is shown in Figure 1 below.
The pressure produced by shock wave can be changed transiently, and the high temperature, strong light and electromagnetism produced by explosion will have a certain impact on the sensor. The ICP-type sensor built-in charge amplification circuit produced by PCB company carries such features like high frequency response, large range and strong anti-interference ability. Thus, the ICP sensor of PCB company is selected as the shock wave pressure sensor. And choosing the LTT184 transient programmable recorder produced by TASLER company as the data acquisition instrument. The composition diagram of the test system is shown in Figure 2.

3. Shock wave test results
A group of data \( \{x_i, y_j, z_{ij}\} \) \( i = 0,1,2,3; j = 1,2,3 \ldots 10 \) is obtained by shooting, in which, \( x \) and \( y \) are the coordinate values of the sensor placement, and \( z \) is the measured pressure value of the sensor at each measuring point. In the actual test, the sensor is placed at the same height as the muzzle, and the sensitive surface of the sensor is vertically upward to examine the grazing incidence shock wave. At the same time, in order to compare the shock wave distribution of the projectile under the high and low temperature conditions, the ammunitions are used to carry out the test respectively. The measured values under the two conditions are shown in Table 1 and Table 2, and we can see the measured values of sensor pressure at coordinates (3, 8) of low temperature ammunition in Figure 3, and the measured values at coordinates (2, 6) of high temperature ammunition in Figure 4.

The specific test results of each point under the low temperature are shown in Table 1.

| X/Y | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|-----|------|------|------|------|------|------|------|------|------|------|
| 0   | 0.0253 | 0.0418 | 0.0913 | 0.1639 | 0.1364 | 0.1023 | 0.1188 | 0.0748 | 0.0539 | 0.0396 |
| 1   | 0.0275 | 0.0407 | 0.0682 | 0.1375 | 0.0814 | 0.0583 | 0.0693 | 0.0517 | 0.0473 | 0.0352 |
| 2   | 0.0308 | 0.0451 | 0.0528 | 0.0682 | 0.0528 | 0.0462 | 0.0561 | 0.0506 | 0.0429 | 0.0363 |
| 3   | 0.0297 | 0.0374 | 0.0462 | 0.0473 | 0.0374 | 0.0341 | 0.0385 | 0.0397 | 0.0363 | 0.0286 |
The specific test results of each point under the high temperature are shown in Table 2.

Table 2. Shock wave pressure values at each measuring point of high-temperature ammunition (MPa)

| X/Y | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0   | 0.0297 | 0.0451 | 0.0913 | 0.2145 | 0.143 | 0.1067 | 0.0957 | 0.0759 | 0.055 | 0.0429 |
| 1   | 0.033 | 0.0495 | 0.0704 | 0.1089 | 0.0913 | 0.0572 | 0.0671 | 0.0517 | 0.0418 | 0.0374 |
| 2   | 0.0352 | 0.0407 | 0.0572 | 0.0638 | 0.0627 | 0.0477 | 0.0627 | 0.0506 | 0.0418 | 0.0319 |
| 3   | 0.0308 | 0.0396 | 0.0506 | 0.0594 | 0.0407 | 0.033  | 0.0319 | 0.0473 | 0.0363 | 0.0297 |

The measured values of sensor pressure at coordinates (3, 8) of low-temperature ammunition and coordinates (2, 6) of high-temperature ammunition can be seen in Figure 3 and Figure 4.

Figure 3. The values of sensor pressure at coordinates (3, 8) of low-temperature ammunition

Figure 4. The values of sensor pressure at coordinates (2, 6) of high-temperature ammunition
From the above test results, it can be seen that the shock wave pressure generated by high-temperature bomb is generally higher than that of the low temperature one; And from a single pressure test point, we can see that the rising velocity of shock wave reaches microsecond level, and there will be multiple peaks in the propagation; In addition, when the Y coordinate is 4, that means 1 m behind the muzzle, the pressure reaches the maximum value, and then the shock wave pressure drops rapidly, and this speed of the shock wave behind the muzzle is obviously greater than that in front of the muzzle.

4. Surface drawing of muzzle shock wave isobaric field

4.1. The selection and algorithm of interpolation function

The drawing of shock wave isobaric surface is inseparable from the selection of interpolation function. Different types of interpolation function will create different interpolation effects. Currently, the commonly used interpolation methods mainly include cubic spline interpolation method, Bessel interpolation method and B-spline interpolation method. Among them, interpolation cubic spline method is an early curve and surface design method, which is relatively basic, and it has many limitations in the practical application. The B-spline method is developed from Bessel method, which carries the geometric properties of Bessel method, and has excellent properties such as locality that Bessel method does not have \cite{8-10}. Consequently, B-spline method is selected as the basic algorithm for drawing the contour of muzzle shock wave. The core of B-spline method is to represent the spatial surface with B-spline function as the base function. The multiplier factor of B-spline basis function is unknown in the expression, and using the least square algorithm to get the best approximation multiplier factor of control grid composed of type value points, we can obtain the B-spline least square fitting surface.

The sensor array is distributed in a rectangular array in two directions perpendicular to each other, as shown in Figure 5.

![Figure 5. Schematic diagram of sensor layout](image)

In the figure, \(x\) represents the horizontal direction, \(n_x\) the number of sensors, \(y\) the vertical direction, and \(n_y\) the number of sensors.

In the region shown in Figure 5, the product partition is: \(\Delta = \Delta_x \ast \Delta_y\), and the node sequence is given:

\[
\begin{align*}
\Delta_x: & \quad Sx_{-k} < Sx_{-k+1} < \cdots < Sx_0 < Sx_1 < \cdots < Sx_{m-1} < Sx_m < \cdots < Sx_{m+k+1} \\
\Delta_y: & \quad Sy_{-l} < Sy_{-l+1} < \cdots < Sy_0 < Sy_1 < \cdots < Sy_{n-1} < Sy_n < \cdots < Sy_{n+l+1}
\end{align*}
\]

(1)

Where \(k\) and \(l\) are the times of \(x\) and \(y\) respectively.

B-spline polynomial function is made for node (1.1)

\[
\begin{align*}
B_{i,l}(x), & \quad i = 1,2,\cdots,m + k + 1 \\
B_{j,s}(y), & \quad j = 1,2,\cdots,n + l + 1
\end{align*}
\]

(2)
Therefore, \( x \) is \( k \) times, \( y \) is \( l \) times, the bivariate B-spline polynomial function of partition \( \Delta \) can be uniquely written as:

\[
S(x, y) = \sum_{i=p}^{p+k} \sum_{j=q}^{q+l} \theta(i, j)B_{i,k}(x)B_{j,l}(y)
\]

(3)

Where, \( p = 1, 2, \cdots, m, m + 1; q = 1, 2, \cdots, n, n + 1. \)

The measured shock wave over-pressure value \( P \) is a function of coordinate \( x \) and \( y \), and it is recorded as \( P(x, y) \), where, \( r = 1, 2, \cdots, n_x; s = 1, 2, \cdots, n_y \). When \( x \) is \( k \) times and \( y \) is \( l \) times, the bivariate B-spline fitting polynomial is constructed:

\[
S(x, y) = \sum_{i=p}^{p+k} \sum_{j=q}^{q+l} \theta(i, j)B_{i,k}(x)B_{j,l}(y)
\]

(4)

Where, \( r = 1, 2, \cdots, n_x; s = 1, 2, \cdots, n_y; p = 1, 2, \cdots, m + 1; q = 1, 2, \cdots, n + 1. \)

At this time, the two-dimensional B-spline least square problem is to solve \( \theta(i, j) \), minimize

\[
\sigma = \sum_{r=1}^{n_x} \sum_{s=1}^{n_y} \left[ S(x_r, y_s) - P(x_r, y_s) \right]^2
\]

(5)

And if \( \frac{\partial \sigma}{\partial \theta(i, j)} = 0 \), then

\[
\sum_{r=1}^{n_x} \sum_{s=1}^{n_y} \left[ S(x_r, y_s) - P(x_r, y_s) \right] \frac{\partial \sigma}{\partial \theta(i, j)} = 0
\]

(6)

When \( n_x \* n_y \geq (m + k + 1) \* (n + l + 1) \), the unique coefficient \( \theta(i, j) \) can be obtained from equation (6), and the B-spline polynomial function \( S(x, y) \) on the known partition will be obtained, and the over-pressure value of any point on the surface can be obtained based on this function.

4.2. Drawing of shock wave pressure surface and isobaric line

According to the above-mentioned B-spline interpolation algorithm and shock wave measurement results, based on Matlab software programming, cubic B-spline curves are used to interpolate in the X and Y directions of sensor distribution, then we can obtain the muzzle shock wave pressure field surface of naval gun in two conditions of launching low-temperature ammunition and high-temperature ammunition, as shown in Figure 6.

(a) Shock wave pressure surface of low-temperature ammunition  
(b) Shock wave pressure surface of low-temperature ammunition

Figure 6. Pressure surface of muzzle shock wave
The three-dimensional pressure surface vividly shows the general distribution of muzzle shock wave in space, but using it to compare and analyze the data is not an easy job. Contour map is used to describe the two-dimensional graph of data in three-dimensional space. The pressure contour map can give us a more intuitive understanding of the overall situation on the one hand, and helps us more accurately understand the distribution of pressure data at all levels in a specific area. Using the muzzle shock wave pressure data, the data interpolation and contour tracking are further carried out to complete the contour map in the sensor layout area. The isobaric line values can be obtained from 0.01Mpa to 0.2MPa, each interval is 0.01Mpa, and the drawing results are shown in Figure 7.

![Shock wave isobaric diagram of high-temperature ammunition](image1)

![Shock wave isobaric diagram of low-temperature ammunition](image2)

Figure 7. Isobaric curve of muzzle shock wave

### 5. Conclusion

In this paper, according to the requirements of a naval gun muzzle shock wave test and the characteristics of shock wave signal, we construct a set of muzzle shock wave test system, and carry out the actual test of high and low temperature ammunition. On this basis, three interpolation methods of isobaric surface drawing are compared and analyzed, and then we use the B-spline to draw the isobaric field surface and isobaric curve of muzzle shock wave. Therefore, the following conclusions can be drawn:

1. From the measured data of muzzle shock wave, it can be seen that the shock wave pressure produced by high-temperature ammunition is generally higher than that of low-temperature one; The maximum pressure appears at 1 m behind the muzzle, and then the shock wave pressure drops rapidly, and this speed of the shock wave behind the muzzle is obviously greater than that in front of the muzzle.

2. From the shock wave is pressure surface and the isopressure curve, we can know that the density of the is pressure line near the axis of the gun mouth is higher than that of other areas, conforming to the distribution characteristics of the shock wave, and verifying the correctness of the test method; When shooting high-temperature ammunition, the density of isobars near the muzzle is much higher than that of low-temperature ammunition. The distribution of isobars can provide an important reference for evaluating the impact of shock wave on equipment and other parts around the muzzle.

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