Experimental study on initial ballistic characteristics of cased telescoped ammunition

Y J Cao, W L Yue, X S Li, Z F Li and J Li

Northwest Institute of Mechanical and Electrical Engineering, Xianyang, Shaanxi, China

E-mail: caoyj801@163.com

Abstract. There is a loading process after the projectile of the cased telescoped ammunition (CTA) fired in the chamber, which has important influence on the stability of interior ballistics, the firing accuracy and the gun barrel life. In order to study the characteristics of velocity and attitude in the initial motion of the projectile of the CTA, a special projectile for the initial ballistic test was designed, and an initial ballistic test system based on the high-speed camera was built. The loading process after firing was observed and the loading velocity was measured. The results show that the loading speed of the projectile is about 30m/s. The initial ballistic parameters of the projectile can be studied quantitatively and the motion attitude of the projectile can be examined qualitatively by using the initial ballistic test system based on the high-speed photography.

1. Introduction

Cased telescoped ammunition (CTA) is a new type of ammunition. Its basic feature is that the projectile is embedded in the cartridge, so that the whole ammunition forms a simple cylindrical shape and the different ammunitions have the same external size, while the total length is greatly shortened compared with conventional ammunitions [1]. The CTA adopts the working principle of the two-stage ignition and the sequential combustion [2], that is, after the primer fires, the quick-burning charge is ignited and the projectile moves in the guide tube until the bearing band is embedded into the rifling. Then, the main charge is fully ignited, producing a large amount of high-temperature and high-pressure gas to accelerate the projectile to the muzzle. The special charge structure of the CTA makes the projectile have a strong impactive loading process in the firing cycle, which mainly affects the following aspects: (1) It affects the motion attitude of the projectile in the bore and the stability of the interior ballistics. (2) The vibration of the barrel is caused, which is ultimately reflected as an influence on the firing accuracy. (3) The severe impactive wear of the bearing band on the initial part of the rifling affects the service life of the barrel.

Previous studies focused on how to improve the interior ballistic performance of the CTA [3-5]. Lu Xin et al. used a transparent chamber to study the ignition and flame spreading characteristics of the CTA [6] and observed the movement process of the projectile under the action of quick-burning charge after ignition. But they ignored the effect of the main charge combustion on the loading velocity of the projectile. The purpose of this paper is to obtain the initial ballistic characteristics of the loading velocity and attitude after the original ignition of the CTA in the bore under the actual charge...
condition, so as to provide a reliable basis for the charge design and subsequent optimization of the CTA.

2. Experiment test system and principle
The initial ballistic test device of the CTA is based on a launcher for the interior ballistic test, which uses a short barrel to make the projectile achieve a velocity far lower than the normal muzzle velocity, so that the initial ballistic characteristics of the CTA can be reproduced well. As shown in figure 1, a thin metal rod is installed on the head of the projectile to ensure that the quality of the tested projectile is the same as that of the formal projectile, so as not to change the initial ballistic performance under the actual charge condition. The front end of the metal rod is treated to form a small area with high reflectivity.

![Projectile for testing the initial ballistic characteristics of the CTA.](image1)

A test system for the projectile initial ballistic characteristics is built based on the high-speed photography (as shown in figure 2) and the test principle is as follows. A black and white block alternate background plate is fixed in the appropriate position parallel to the barrel axis. A high speed camera is fixed in front of the background plate, to make sure that the high-speed camera view can cover the whole background plate, and the projection of the metal rod head is in the background plate. After the firing of the test device, the computer begins to record the initial ballistic process of the projectile, and the image processing software processes the high-speed photographs to obtain the motion velocity of the projectile.

![Schematic diagram of the initial ballistic test system of the CTA](image2)

3. Data processing method

3.1. Image processing method
Pixel coordinate system $uov$ is a two-dimensional rectangular coordinate system that reflects the arrangement of pixels in the camera CCD/CMOS chip. The origin $o$ is located in the upper left corner of the image, and the $u$-axis and the $v$-axis are parallel to the both sides of the image plane. The units of the coordinates in the pixel coordinate system are pixels (integers). The pixel coordinate system is not conducive to the coordinate transformation, so the image coordinate system $XOY$ needs to be established. The unit of its coordinate axis is mm, and the transformation relation is
Where, $K_1$ is the physical size of the pixel, and $(u_0, v_0)$ is the coordinate of the main point.

\[ \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} 1/K_1 & 0 & u_0 \\ 0 & 1/K_1 & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} \]  \hspace{1cm} (1)

Figure 3. Schematic diagram of the perspective projection of the coordinate system.

The relationship between any point $P$ in the space and its image point $p$ is shown in figure 3. The connection line between $P$ and the optical center of the camera is $oP$, and the intersection point $p$ between $oP$ and the image plane is the projection of the spatial point $P$. Where, $x_c$-$y_c$-$z_c$ is the camera coordinate system, that is, the cartesian coordinate system in the physical space with the camera optical center as the origin. According to the similar triangle principle, the camera coordinate system and the image coordinate system can be transformed as follow

\[ z \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} \]  \hspace{1cm} (2)

Where, $f$ is the focal length of the camera.

Figure 4. Schematic diagram of the angle correction for the reference plane.

Before the experiment, a background plate with grids was set as the reference plane, which was not strictly perpendicular to the $z_c$ axis of the camera coordinate system (as shown in figure 4). To facilitate data processing, the reference plane is rotated around its intersection line with the $z_c$-$y_c$ plane to obtain the corrected reference plane. The distance between the intersection point and the origin of the camera coordinate system is $H$. On the reference plane, Equation (2) can be simplified as follow
\[
\begin{bmatrix}
X \\
Y
\end{bmatrix} = \begin{bmatrix}
f & 0 \\
0 & f/H
\end{bmatrix} \begin{bmatrix}
x'_c \\
y'_c
\end{bmatrix}
\]

(3)

Where, \((x'_c, y'_c)\) is the mapping of the point \((x_c, y_c)\) on the reference plane to the correction plane. According to the sine theorem we can obtain that

\[
x_c \cos \alpha = \frac{x'_c}{\cos(\alpha + \beta)}
\]

\[
y_c = y'_c
\]

(4)

(5)

The difference between simultaneous equations (1), (3), (5) and (4) is

\[
\begin{bmatrix}
u \\
v
\end{bmatrix} = \begin{bmatrix}
f/H \cdot K_1 & 0 & u_0 \\
0 & f/H \cdot K_1 & v_0
\end{bmatrix} \begin{bmatrix}
x_c \frac{\cos(\alpha + \beta)}{\cos \alpha} \\
y_c \\
1
\end{bmatrix}
\]

(6)

Since the background grid plate is not placed perpendicular to the ground, the image of the grid in the vertical direction \((y_c\) axis) will be compressed and the \(dy_c\) distortion will occur. Therefore, only the differential dimension of the horizontal \((dx_c)\) is used for the calculation reference.

3.2. Processing method for initial ballistic velocity and acceleration of projectile

Through target recognition, we can find the position \(x_i\) of the projectile head vertex corresponding to \(t_i\). The velocity and the acceleration of the projectile at this time are obtained by interpolation

\[
v_i = \frac{x_{i+1} - x_{i-1}}{2 \Delta t}
\]

\[
a_i = \frac{v_{i+1} - v_{i-1}}{2 \Delta t}
\]

(7)

(8)

Where, \(i=2, 3\cdots, n-1\).

3.3. Processing method for initial ballistic swing angle of projectile

In order to investigate the in-bore swing attitude of the projectile in the initial ballistic process (before the bearing band is embedded into the riffling), the change of the pitch angle is studied. As shown in figure 5, in the section observed by the high-speed camera, the extension line of the projectile axis when the cartridge is loaded in place is taken as the benchmark, indicating that the upward inclination is positive and the downward inclination is negative.

![Figure 5. Schematic diagram of the projectile pitch inclination.](image)
The front centroid coordinate \((x_1, y_1)\) and the tail centroid coordinate \((x_2, y_2)\) can be obtained by the following formula:

\[
x = \frac{\sum_i m_i x_i}{\sum_i m_i} \tag{9}
\]
\[
y = \frac{\sum_i m_i y_i}{\sum_i m_i} \tag{10}
\]

In which, \(m_i\) is the gray value of the binarization graph at the \(i\)th point, and \((x_i, y_i)\) is the coordinate position of the \(i\)th point. Then the slope of the target can be calculated

\[
k = \frac{y_2 - y_1}{x_2 - x_1} \tag{11}
\]

Then the inclination angle in the initial ballistic stage of the projectile is

\[
\theta = \arctan(k) \tag{12}
\]

4. Experimental result and analysis

According to the data processing method described in the previous section, the high-speed photographic image is processed. The typical displacement, velocity and acceleration parameters of the same shot projectile changing with time are shown in figure 6. To facilitate the observation of the motion parameters of the projectile at a certain position, the displacement of 100mm is selected as the characteristic point, as shown in the red triangle in the figures. The displacement - time curve of the projectile under test is smooth, which truly reflects the initial ballistic motion law of the projectile.

![Figure 6. Typical curves of displacement, velocity and acceleration of the tested projectile over time.](image)

The displacement, velocity and acceleration curves of a group of 5 shots over time are shown in figure 7. The distance of the projectile from the initial position to the rifling embedded in the bearing band is 20mm. During this process, the acceleration of the projectile is random, and the acceleration value fluctuates within the range of 1000–16000 m/s², which may reveal the instability of the gas pressure in the bore at the initial ballistic stage. However, when the projectile is just right embedded into the rifling, the corresponding velocity is maintained at about 30m/s. In the following period of about 0.5ms, the acceleration of the projectile shows a gradual upward trend, up to a maximum of about \(4 \times 10^5\) m/s². During this period, the displacement of the projectile is about 100mm, and the movement velocity increases sharply, from about 30m/s to about 250m/s. At this stage, the projectile enters the stable acceleration stage in the bore. In the next stage, the projectile has flown out of the muzzle of the initial ballistic test device and entered the aftereffect period. The velocity increases slowly and gradually reaches the maximum, while the acceleration drops sharply.
Figure 7. Curves of displacement, velocity and acceleration of a tested projectile group with time.

The typical pitch inclination of the tested projectile is shown in figure 8. There is an obvious trend of variable periodic fluctuation. The reasons may be that: (1) during the period of acceleration in the bore, the uneven distribution of the gas at the bottom of the projectile and the gap between the centering part of the projectile and the barrel, cause the projectile to generate the pitching inclination; (2) as the projectile rotates, the inclination angle of the projectile axis deflects, and the inclination angle decreases first and then increases. Because the high speed photographic image only records the change of the pitch inclination in one section, and there is a problem of projection distortion, it can not accurately reflect the projectile motion attitude, only the projectile motion attitude can be observed qualitatively.

Figure 8. Typical curve of the projectile pitch inclination with time.

5. Conclusions
(1) Within about 0.8ms after the projectile is started, the projectile motion acceleration has certain randomness, which may reveal the instability of the gas pressure in the chamber at the initial ignition stage. And the loading speed of the projectile is about 30m/s.
(2) The high-speed photography is scientific and effective in quantitatively examining the motion parameters of the displacement, velocity and acceleration in the initial ballistic process. However, due to the problem of the observation angle, the high-speed photography can only be used to qualitatively observe the projectile's initial motion attitude, so the projectile attitude testing method needs to be further improved.

References
[1] Farrand T G 2000 Initial Evaluation of the CTA International 40-mm Cased Telescoped Weapon System ARL-TR-2275
[2] Zhang H, Lu X and Yu Y G 2006 Acta Armamentarii 27(4) 630-3
[3] Wang J G, Yu Y G and Guo F 2015 Journal of Ballistics 27(2) 69-73
[4] Wang J G, Yu Y G and Zhou L L 2018 Defence Technology 14 119-25
[5] Lu X, Zhang H and Zhou Y H 2008 Journal of Nanjing University of Science and Technology 32(6) 690-4
[6] Lu X, Zhou Y H and Yu Y G 2010 *Journal of Applied Mechanics* **77** 051402-1-051402-5