Multiple feature time extraction and match recognition of projectile in velocity measurement system based on dual active photoelectric detection sensors

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The external factors influence the performance of the active photoelectric detection sensor (APDS) to recognize the real projectile signal and reduce the velocity measurement accuracy of the system. Based on detection mechanism of APDS, the calculation model of the laser reflection energy of the projectile's surface is established and the output signal voltage function of APDS is deduced; The time extraction method of projectile signal based on wavelet transform modulus maximum is developed, the double constraint model composed of the same projectile time matching criterion and the correlation coefficient of double parallel laser detection screens are formed. The experiments are carried out in different interference environments, the test results show that the time extraction method proposed in this paper can obtain accurate test data. Moreover, when multiple projectiles are continuously fired, combined with the double constraint model, the time information of the same projectile passing through the two laser detection screens can be matched and the velocity of each projectile can be accurately obtained, which can effectively reduce the influence of external factors on the velocity measurement system based on dual APDSs.

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1. Introduction

For the high radio frequency continuous firing weapon (HRFCFW), the flight velocity of multiple projectiles is an important parameter to measure the kinetic energy of the projectile at a certain time and can evaluate the damage effect of the HRFCFW on the target [1-2]. Currently, the equipment for measuring the projectile velocity mainly focuses on the sky-screen and light-screen measurement systems [3-4]. The sky-screen measurement system arranges two sky-screens on the trajectory of the predetermined firing position of the weapon. When the projectile passes through the two detection screens, the signal acquisition device collects the signals of the projectile. The flight velocity of the projectile is calculated by signal filtering processing and time recognizing extraction. The light-screen measurement system mainly uses the line array LED and the line array semiconductor photoelectric receiver to form two light screens that are parallel to each other and separated by a distance. When the projectile passes through the two light screens, the projectile information is recognized and the time information is recorded, then the velocity of the projectile is obtained. Due to the obvious random vibration generated at the moment of weapon firing, the spatial dispersion of continuous firing multiple projectiles is a random distribution state; the signals collected by the test equipment are often accompanied by various types of interferences, which belong to non-stationary random signals. At the same time, the test equipment also has inherent noise that affects the projectile signal recognition and diagnosis. Since there is a certain error in the charge amount of each projectile fired by the HRFCFW, the velocity of each projectile is different during weapon firing, resulting in the latter projectile exceeding the previous projectile for the flight projectiles through the same detection screen. This phenomenon easily causes errors in the test results if the time of the projectile signal is still extracted in sequence, and brings difficulties in testing multiple projectile velocities of the HRFCFW.

The multiple projectile signal recognition method generally adopts the methods of human manual and automatic hybrid recognition processing. Zhang et al. [5] introduced a correlation function method for recognizing and processing simulated multiple projectile signals. Li et al. [6] proposed a warhead fragment recognition method using a correlation coefficient. Yang et al. [7] studied the warhead fragment signal feature test method to obtain the velocity of warhead fragment based on the laser detection screen test system. Lou et al. [8] utilized the Hopfield auto-associative neural network to develop a sky-screen signal recognition method. The above-mentioned methods effectively improve the recognition ability of the test system. The sky-screen is mainly used in the field, its detection performance is significantly affected by the environmental illumination and it can hardly detect the signal under low environmental illumination conditions. However, the sky-screen has the advantages of simple structure, large detection area and convenient layout. Moreover, the sky-screen is still an important test device for external ballistic velocity measurement of the current weapon systems. Based on the sky-screen, a high-power laser is added and the fan-shaped light source plane of the laser is formed, this plane is adjusted to coincide with the receiving and detecting plane of the sky-screen, an active photoelectric detection sensor (APDS) is developed in this paper, the APDS is a photoelectric detection sensor with an active light source. The detection principle of the proposed APDS is to use the laser energy reflected by the projectile's surface as the basis for recognizing the projectile signal. Since the power of the laser is slightly affected by the environment, the projectile can still be detected by the APDS at night. Compared with the sky-screen, the detection ability of the APDS is increased under low environmental illumination, and it can work day and night, the use of laser improved the detection performance of sky-screen. In addition, the signal output by the photoelectric receiving and detection plane is superimposed with the laser radiation signal, which increases the difficulty of projectile signal recognition and time extraction, so the mathematical model of reflected laser energy and the projectile signal time extraction method based on wavelet modulus maximum singular points are studied. The flight velocity constraint criterion of the projectile is established to effectively reduce the influence of external interference on the velocity measurement system.

2. Projectile's velocity measurement system based on dual active photoelectric detection sensors

The projectile's velocity measurement system based on dual APDSs is composed of two APDSs, an acquisition module and a processing computer, as shown in Fig. 1.

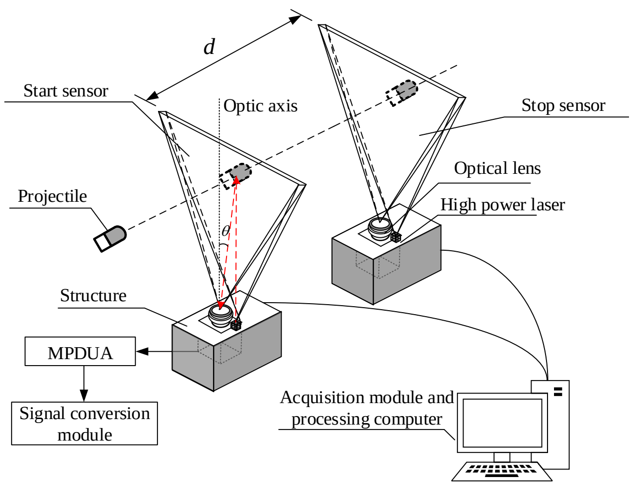

Fig. 1. Projectile's velocity measurement system based on dual APDSs

In Fig. 1, two APDSs are called start sensor and stop sensor, the start sensor is close to the weapon firing position, and the time of projectile passing through its LDS is defined as the start time. The APDS is composed of an optical lens, slit diaphragm, multiple photoelectric detection units array (MPDUA), signal conversion module and high-power laser. Slit diaphragm, MPDUA and signal conversion module are placed in the structure, slit diaphragm is placed under the optical lens, the MPDUA is placed is placed between the slit diaphragm and signal conversion module, the photoelectric detection receiving light path is formed by the slit diaphragm mapping in the air through the optical lens. The MPDUA is composed of multiple photoelectric detection units that are spliced together to form a long strip-shaped detection surface. The MPDUA can expand the detection surface compared with the unit photoelectric detector. The MPDUA and the signal conversion module are connected, the signal conversion module can output the signal detected by the MPDUA. The high-power laser and the photoelectric detection receiving light path form a laser detection screen (LDS). Two LDSs are perpendicular to the trajectory through adjustment, parallel to each other and separated by a certain distance.

When the projectile passes through the test area, the laser energy is reflected by the projectile's surface, and sensed by the MPDUA to form a changeable signal. Through projectile signal filtering processing and feature point extraction, the time of the projectile through each LDS can be recorded. The recorded times t_1 and t_2 are obtained when the projectile passes through the start sensor and the stop sensor, respectively. If d is the distance between the start sensor and the stop sensor, the flight velocity of the projectile can be expressed as:

$$v = d / (t_2 - t_1) \tag{1}$$

It can be seen from Formula (1) that accurate velocity information can be obtained by extracting the accurate time value. Since the PDS adopts a laser with an active light source, it forms an ALDS. The stability of its light source and the dust particles in the environment inevitably affect the output signal of the APDS. Therefore, the projectile signal characteristic model of the APDS is mastered and the feature points of the real projectile signal are extracted.

3. The calculation model of laser reflection energy on projectile's surface

It can be found from the projectile's velocity measurement principle in Fig. 1 that the laser reflection energy on the surface of the projectile is generated when the projectile passes through the test area. The distance between the projectile and the center point of the optical axis of lens is called the detection distance. When the detection distance is relatively close, the laser reflection energy is relatively strong and the amplitude of projectile signal output by the APDS is large and reaches the maximum value. In contrast, the amplitude of the projectile signal is small when the detection distance is relatively far. Thus, the laser reflection energy is related to the detection distance when the laser emission power is determined.

The distance between the laser and the optical lens is relatively small compared to the detection distance. Therefore, the distance is ignored in this paper and the laser and the optical lens both are regarded at the same position. When the projectile passes through the LDS, the laser irradiates the projectile's surface and the laser reflection energy is detected by the MPDUA. The laser reflection energy is related to the position of the projectile passing through the LDS. Assuming that there is an intersection angle θ between the laser beam irradiated on the surface of the projectile and reflected into the optical lens, the spot plane reflected onto the MPDUA also forms the same intersection angle θ with the reflected laser beam. If the laser beam is vertically reflected onto the MPDUA and forms the spot area A_0, this moment, the spot area is $A_0/cos\theta$, which can be equivalent to the receiving window size of the optical receiving system. The laser reflection power can be calculated by Formula (2).

$$P(R) = \frac{P_0\sigma(\theta,\phi)\cdot A_0 / \cos\theta \cdot \tau_0 \exp(-2\tau_1 R)}{4\pi r^2 \cdot R^2} \quad (2)$$

In Formula (2), P_0 is the peak of the laser emission power, $\sigma(\theta,\phi)$ is the laser scattering cross-section model, ϕ is the diameter of the equivalent circular area of the projectile cross-section, τ_0 is the transmittance of the optical system, τ_1 is atmospheric transmission attenuation coefficient, R is the detection distance and r is the radius of the equivalent circular area of the intersection between the laser and the projectile [9-10].

The MPDUA receives the laser energy reflected by the projectile's surface and then converts it into a photoelectron number that is expressed as:

$$n_e = \frac{\kappa\cdot P(R)\cdot T}{hc/\lambda} = \frac{\kappa\cdot P_0\sigma(\theta,\phi)\cdot A_0\cdot\tau_0 \exp(-2\tau_1 R)T\lambda}{4\pi r^2\cdot R^2\cdot hc\cdot\cos\theta} \quad (3)$$

In Formula (3), κ is the photoelectric conversion efficiency, T is the duration time that the projectile passes through the LDS, λ is the laser wavelength, h is the Planck constant and c is the velocity of light. The photoelectron number is converted into a voltage function as:

$$V_{out}(t) = \frac{R_{i-eq}A_u\kappa P_0\sigma(\theta,\phi)\cdot A_0\cdot\tau_0 \exp(-2\tau_1 R)T\lambda}{4\pi r^2\cdot R^2\cdot hc\cdot\cos\theta} \quad (4)$$

In Formula (4), R_{i-eq} and A_u are the equivalent impedance and the gain of the detection circuit, respectively. When the detection distance is different, the duration time T is also different and is a dynamic variable [11]. From Formula (4), it can be seen that the output voltage of the multiple photoelectric detection units array is proportional to the laser emission power and the gain of detection circuit. For the same type of projectile, the amplitude of the output voltage of the multiple photoelectric detection units array decreases gradually with the increase of the detection distance. If the gain of the detection circuit and the laser emission power are increased without limit, not only the amplitude of output voltage of the multiple photoelectric detection units array is increased, but also the inherent noise of the system is increased; If the inherent noise of the system increases more, the signal-to-noise ratio of the system will be reduced, which is not conducive to improving the detection ability of the system. Therefore, the premise of the increase of the gain of the detection circuit and the laser emission power is that the signal-to-noise ratio of the system is improved. The gain of the detection circuit in the system can be appropriately increased, and the laser emission power of the active light source can be increased to ensure the reliable detection of the system and improve the detection ability of the system.

4. Multiple feature time extraction algorithms of the projectile through laser detection screen

4.1. Filtering and processing algorithms on the projectile signal

After the weapon launches the projectile, the acquisition module of the system receives the acquisition command, starts to collect the signal, and provides the information containing the projectile signal. Assuming that $y(t) = V_0(t) + N_0(t) = V_{out}(t)$, $V_0(t)$ is a projectile signal without noise and $N_0(t)$ is the noise signal contained in the signal, $y(t)$ is processed by the wavelet transform as:

$$W(a,\tau) = \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} y(t)\varphi^*(\frac{t-\tau}{a})dt \quad (5)$$

In Formula (5), a and τ are the scale and time shift factors, respectively, and $\varphi^*(\frac{t-\tau}{a})$ is the conjugate function of the mother wavelet function $\varphi(t)$. $y(t)$ is expressed as $y(k)$ after discretization, among, k is the discrete sampling point of signal, the wavelet scale coefficients $b_{n,m}$ and the wavelet coefficients $c_{n,m}$ are obtained through orthogonal wavelet decomposition. The wavelet reconstruction function is:

$$b_{n,m} = \sum_k b_{n+1,k}A(m-2k) + \sum_k c_{n+1,k}B(m-2k) \quad (6)$$

In Formula (6), $A(m-2k)$ and $B(m-2k)$ are the low-pass and high-pass filter coefficients used to obtain the low-frequency smoothing profile A_n and the high-frequency detail part B_n, respectively, while n is the number of wavelet decomposition layers, and $n=1,2,3,\cdots$. According to the signal characteristics of the projectile, the Daubechies wavelet is used to decompose the projectile signal into six layers, and the high-frequency component of the projectile signal is obtained by adjusting the different scale coefficients [12-13].

The wavelet coefficients are used to eliminate the high-frequency components of the projectile signal. The wavelet coefficients $\omega_{n,m}$ of the projectile signal are divided into two parts, and $\omega_{n,m}=q_{n,m}+u_{n,m}$, where $q_{n,m}$ and $u_{n,m}$ are the wavelet coefficients expressing the projectile and noise signals, respectively. The wavelet threshold method is used to remove the noise signal. The Daubechies wavelet base is selected for decomposition, and the noise signal is transformed into the wavelet domain by orthogonal discrete wavelet, a set of wavelet coefficients $\omega(n,m)$ is obtained. In this paper, the hard threshold function is selected and its threshold voltage is V_T. If $|\omega|>V_T$, the signal characteristics will be retained and if $|\omega|\le V_T$, the signal characteristics will not be retained. According to the national standard of weapon shooting range test, the output signal of the photoelectric detection module in the laser detection sensor is generally selected to be 2 times greater than the noise voltage, which is defined as capturing the projectile information. Assuming that the noise voltage of the system is expressed by V_s, if the photoelectric detection system is to detect the projectile information, it must meet $V_T/V_s>2$, V_T is the minimum voltage that the photoelectric detection system can recognize the signal, also known as the threshold voltage. The wavelet coefficients of the original signal $\omega'(n,m)$ are obtained using the hard threshold function to deal with $\omega(n,m)$ and make $|\omega'(n,m)-\omega(n,m)|$ small. Then $\omega(n,m)$ is used for wavelet reconstruction, the estimated signal after denoising is obtained and $y'(t)$ is the filtered signal containing projectile information.

4.2. Multiple feature time extraction algorithms

The Lipschitz exponent C can describe the singularity of $y(t)$ at point t_0. If i is a non-negative integer, and $i\le C\le i+1$, only if there are two constants Q and G', $G'>0$, and $G\le G'$, so

$$\left|y(t_0+G)-y_i(G)\right|\le Q\left|G\right|^C \tag{7}$$

In Formula (7), C is called the Lipschitz exponent of the projectile signal $y(t)$ at point t_0 when the projectile passes through the LDS. The derivative order of $y(t)$ at point t_0 is higher, the C is greater, and the smoother the projectile signal at point t_0. If $C<1$, $y(t)$ has a singularity at point t_0.

Assuming that the mother wavelet function $\varphi(t)$ has a vanishing moment of i-order, $i>0$, and i is a positive integer, $C\le i$, there is Lipschitz exponent C at point t_0 and there is a constant ε in the neighborhood of the point t_0 and all scales, which make the wavelet transform of the projectile signal satisfy the Formula (8).

$$\left|Wf(b,t)\right|\le\varepsilon(b^C+\left|t-t\right|^C) \tag{8}$$

The singular points of the projectile signal are distributed on the modulus extreme value line of the signal wavelet transform, and the Lipschitz exponent $C<1$. The projectile signal has a singularity, and the Lipschitz exponent $C>0$. Thus, the wavelet transform method is used to detect the signal singularity of the projectile passing through the LDS. If the point is not a local singular point of $y(t)$, the point satisfies the relations in the left and right neighborhoods:

$$\left|Wf(b',t)\right|\le\left|Wf(b',t_0)\right| \tag{9}$$

In Formula (9), (b',t_0) is the modulus maximum point under the scale b' of $\left|Wf(b',t)\right|$, and $\left|Wf(b',t_0)\right|$ is the corresponding modulus maxima. The singular point caused by the projectile signal can be located for the collected projectile signal. The wavelet transform is used for multi-scale analysis. The modulus maximum of the projectile signal is used to determine the singular point, and the time t is found by the scale b'. The filtering processing and time extraction of any projectile signal are realized [14-15].

5. Match recognition method of projectile in the velocity measurement system

5.1. Time constraints relationship of two active photoelectric detection sensors

The time is obtained using the multiple feature time extraction method of the projectile signal. However, in the velocity measurement system based on dual APDSs, the time extraction method will inevitably affect the determination of the modulus maximum of the projectile signal due to the existence of random interference signal, it is necessary to establish the projectile velocity constraint criterion to recognize the real projectile signal. Different flight projectiles have different dynamic parameters, especially the velocity parameters. For the same type of weapons, the velocities of projectiles are within a certain range. Assuming that the velocity range of the same type of projectiles is $(v_{\min}, v_{\max})$, d is known in Fig. 1, so the shortest time $\Delta t_{\min}$ and the longest time $\Delta t_{\max}$ for the projectile to pass through two LDSs can be calculated as:

$$\Delta t_{\max} = d / v_{\min} \tag{10}$$

$$\Delta t_{\min} = d / v_{\max} \tag{11}$$

For the projectile signal, the maximum value of the signal singularity point is determined to obtain the starting time when the projectile passes through the LDS. The projectile signal rising and falling processes are symmetrical. It is assumed that C is the singularity Lipschitz exponent at point t_0 of $y(t)$, $C \in (0,1)$, and satisfies Formulas (7)-(9), the maximum value points corresponding to the sampling points k_0 and k_1 for the rising and falling processes of the projectile signal can be determined, respectively. Then, it can be defined as the effective width Δt of the projectile passing through the LDS, and $\Delta t = (k_1 - k_0)/f$. f is the sampling frequency of acquisition module, Δt should be satisfied $\Delta t_{\min} \le \Delta t \le \Delta t_{\max}$. Since the detection ability of two APDSs is consistent, the time width is also consistent for the same projectile through two LDSs, that is, $\Delta t_A = \Delta t_B$, the duration times of start sensor and stop sensor are Δt_A and Δt_B, respectively. Obviously, the signal width of the projectile passing through the LDS can be found by extracting the feature points of the projectile signal, which can effectively eliminate the interference of external signals.

5.2. Correlation matching recognition method of two laser detection screen planes

Because the thickness of the LDS is relatively thin, the waveforms of the projectile passing through each LDS are similar. It can be seen from the layout of Fig. 1 that the waveforms of the projectile passing through parallel LDSs have a strong correlation. Let M_1 and M_2 be parallel LDSs that are related to each other. By using the correlation of signal waveform, the attribution relationship of parallel LDSs to the same projectile waveform is obtained. If $y_{1q}(t)$ is defined as the signal of the q-th projectile passing through M_1 and $y_{2p}(t)$ is defined as the signal of the p-th projectile passing through M_2. Their correlation coefficients are:

$$\delta_{12} = \frac{\mathrm{cov}(y_{1q}(t), y_{2p}(t))}{\sqrt{D[y_{1q}(t)]} \cdot \sqrt{D[y_{2p}(t)]}} = \frac{\sum [y_{1q}(t) - E(y_{1q}(t))][y_{2p}(t) - E(y_{2p}(t))]}{\sqrt{\sum [y_{1q}(t) - E(y_{1q}(t))]^2} \cdot \sqrt{\sum [y_{2p}(t) - E(y_{2p}(t))]^2}} \tag{12}$$

The recognition processing algorithm of the projectile signal is:

(1) The signal is obtained by a multi-channel acquisition module and is filtered by the discrete wavelet transform.

(2) According to Formula (12), the correlation coefficient of the signal at different channels is calculated and the attribution corresponding relationship of the projectile signals is obtained. If the correlation coefficient of M_1 and M_2 is the largest, namely, δ_{12} is the largest, then $y_{1q}(t)$ and $y_{2p}(t)$ are the correlation waveforms, which can be considered as the output signals of the same projectile.

(3) The time of the projectile passing through M_1 and M_2 is obtained as t_{1q} and t_{2p}, respectively, using the wavelet transform modulus maxima time extraction method. Thus $t_{1k} = t_{1q}$ and $t_{2k} = t_{2p}$ are the times of the same projectile.

6. Calculation and test analyses

6.1. Calculation analysis

According to the detection principle of APDS, the focal length and the detection effective field of view of the optical lens are selected as 50 mm and 41°, respectively, and the optical aperture is 1:1.8. The slit diaphragm is 0.2 mm × 42 mm, the response spectrum range of MPDUA is 480 nm-1100 nm and the response time is 0.1×10^{-7} s. The peak of laser emission power is adjustable between 25 W and 45 W, and the effective field of view of the laser is consistent with that of the optical lens. For APDS, the main factors affecting the detection ability mainly come from the laser emission power, the size of projectile and the gain of the detection circuit. If the gain of the detection circuit is determined, the projectile's size affects the effective laser reflection energy.

In order to scientifically analyze the detection performance of the system, this paper uses the projectile fired by an air gun as the target for calculation and testing. The projectile is 5.6 mm in length and 4.5 mm in diameter with a theoretical velocity of 145 m/s. For the photoelectric detection sensor, its detection ability index is often measured by the multiple of the diameter of the detected projectile. If the diameter of the detected projectile is 4.5 mm and the detection ability of the photoelectric detection sensor is 800 times the diameter of the projectile, then the maximum detection distance of the photoelectric detection sensor is 3.6 m; therefore, when the detection distance exceeds 3.5 m, it is also close to the maximum detection distance of the system. At this time, the amplitude of the laser reflection energy and voltage output by the system is relatively small. If the amplitude of the voltage output by the system is slightly greater than the threshold voltage, the system can detect the projectile signal; with the further increase of the detection distance, the amplitude of the voltage output by the system will be less than the threshold voltage. Because the ratio of the projectile signal to the noise signal is less than 2, the system cannot detect the projectile signal at this time.

According to Formula (2), the contribution of the laser energy reflected by the projectile’s surface is mainly determined by the laser emission power and the detection distance. Fig. 2 shows the relationship between the laser reflection energy and the detection distances. Fig. 3 shows the relationship between the output projectile signal voltage and detection distance.

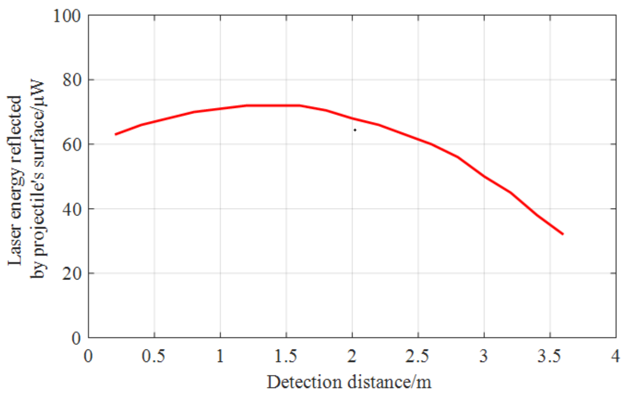

Fig. 2. The relationship between the laser energy reflected by the projectile's surface and the detection distance

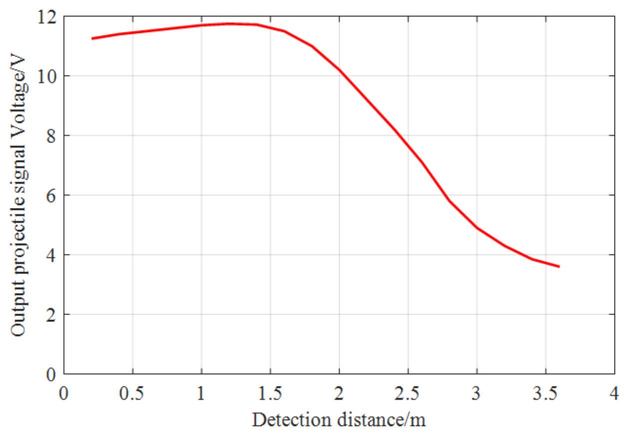

Fig. 3. The relationship between the output projectile signal voltage and the detection distance

It can be found from Fig. 2 that the change in detection distance causes a nonlinear change in the effective laser reflection energy of the surface of the projectile. According to the designed slit diaphragm and the size of the tested projectile, when the thickness of the LDS of APDS is consistent with the length of the projectile, the corresponding detection distance is about 1400 mm. When the detection distance is greater than 1400 mm, the cross-sectional area of the projectile reflected laser in the LDS is unchanged with the increase of the detection distance. However, the laser energy distribution, the laser reflection energy, and the peak of the projectile signal output by the system decrease with the increase in detection distance. From Figs. 2 and 3, the interference source of APDS is mainly other non-projectile surface reflection information, such as mosquitoes and dust particles in the air. These false projectiles are caused by the test environment. The real projectile signal is effectively recognized, which is an important part of effectively improving the reliability of the measurement system.

6.2. Test analysis

According to the velocity measurement principle in Fig. 1 and given parameters of the system, the distance between two APDSs is 5.63 m. The acquisition card is used to collect the projectile signals. The sampling frequency is 2 MHz and the laser emission power is 45 W. The weapon uses the vertical detection screen to shoot, and the firing position of the weapon is about 1.52 m away from the ground. Fig. 4 shows a projectile signal collected in the test under the environmental illumination condition of 1080 lx. The projectile signals of start sensor and stop sensor are collected by the the acquisition card, CH1 and CH2 show the projectile signals when the projectile passes through two LDSs, and then the collected signals are filtered and the processing results are shown in Fig. 5.

It can be seen from the waveform in Fig. 4 that when the environmental illumination is 1080 lx, the APDS can still effectively detect the projectile signal compared with the sky-screen, because when the environmental illumination is lower than 1500 lx, the detection ability of the sky-screen has declined sharply, see Ref. [16] for the detection performance of sky-screen. Although the environment has no significant impact on the APDS, the output of the APDS still has certain interference signals, in Fig. 4, CH1 outputs two signals and CH2 outputs one signal, among, CH1 contains a false projectile signal. For the MPDUA, it can not only detect the projectile signal, but also detect the interference signal when the projectile passes through the detection screen.

The time extraction algorithm of modulus maxima of wavelet transform signal singularity is used to extract the time of projectile signals output by two APDSs, the signal processing results is shown in Fig. 5.

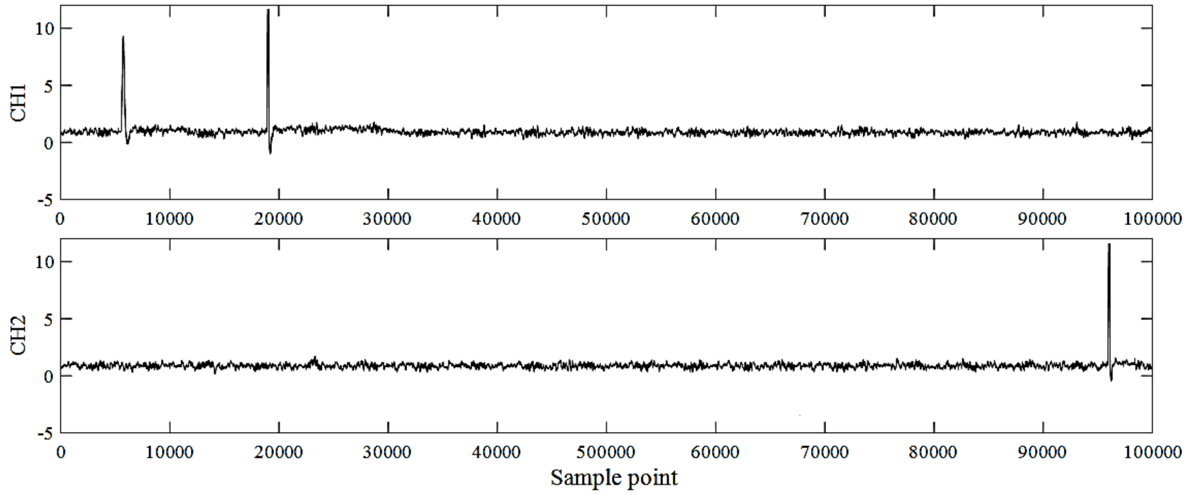

Fig. 4. The signals output by two APDSs

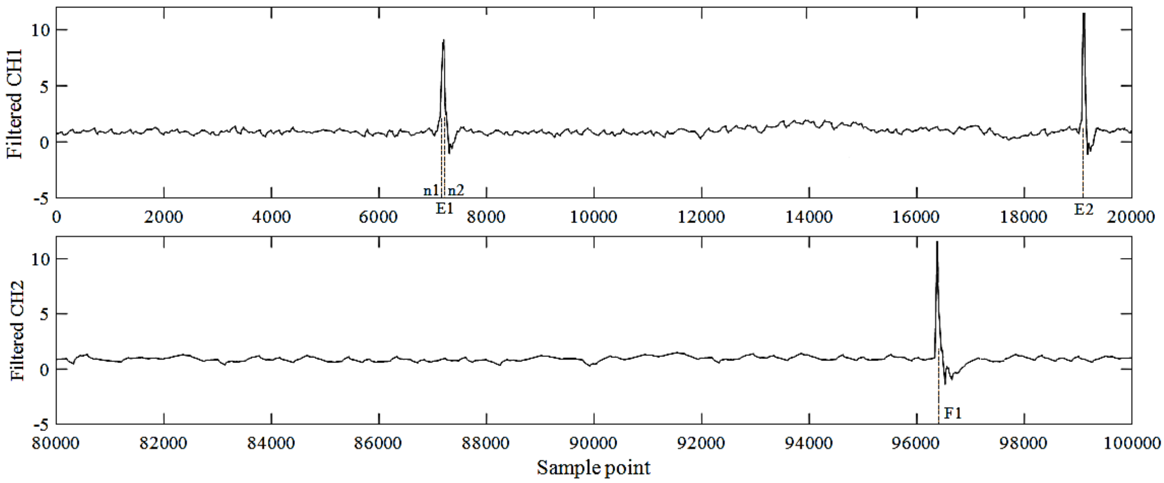

Fig. 5. The signal processing results of two APDSs

In Fig. 5, for the waveform of CH1, n1 and n2 are the points where the positive and negative mode maxima converge, respectively. According to the Lipschitz exponent, there are $0 \leq C \geq 1$. Since the positive and negative mode maxima do not converge to the same point, the average value is considered as the characteristic point at the starting time of the projectile passing through the LDS, and the recorded 6718 on the abscissa is the sampling point E1. According to the sampling frequency of the acquisition module, the recorded time is 3.359 ms at 6718 on the abscissa. The convergence point of the modulus maximum of the second peak signal is 19204, the recorded time is 9.602 ms, and it is recorded as E2. Similarly, for the signal of CH2, the time extraction and processing method of modulus maxima of the wavelet transform signal singularity is used to obtain the convergence point of modulus maxima of peak signal, which is 96441. The recorded time is 48.221 ms, and is expressed by F1. The distance between the two APDSs is 5.63 m, if the E1 is the time of real projectile signal, the time difference between points E1 and F1 is 44.862 ms, so the flight velocity of the projectile is 125.49 m/s; if the E2 is the time of real projectile signal, the time difference between points E2 and F1 is 38.619 ms and the flight velocity of the projectile is 145.78 m/s. According to the projectile velocity convention criterion Formulas (10) and (11), it is not difficult to judge the time difference between points E2 and F1. Therefore, point E1 is a false projectile point. It can also be seen from this test that there are some differences between the two signals of CH1, which fully reflect the different reflection energies from the waveform at points E1 and E2. At the same time, it can also be seen that the signal at point E2 is similar to the signal of CH2 at point F1.

To further verify the scientificity of the match recognition method of the system, the velocity of a group of continuous firing projectiles is tested. The weapon still uses the vertical detection screen to shoot and the firing position is about 2.37 m away from the ground. The environmental illumination is reduced to 650 lx and the laser emission power remains unchanged at 45 W. The actual number of projectiles fired is five. Fig. 6 shows the collected signals in CH1 and CH2.

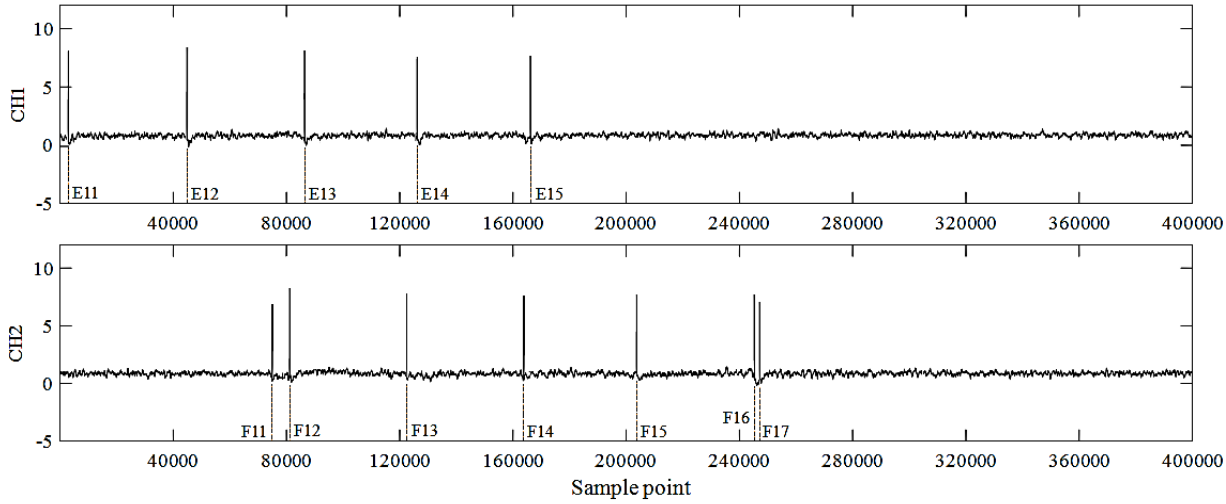

Fig. 6. The collected signals

The time of the signals of CH1 and CH2 are obtained according to the time extraction algorithm of the modulus maxima of wavelet transform signal singularity. The five signals of CH1 are recorded as E11-E15 in order, and the seven signals of CH2 are recorded as F11-F17 in order. Table 1 gives the time data of each signal, among, the unit of time is ms.

Table 1. The time data

Channel number	Signal and Time						
CH1	E11	E12	E13	E14	E15		
	2.06	22.155	42.285	62.36	82.465		
CH2	F11	F12	F13	F14	F15	F16	F17
	37.915	40.67	61.36	81.57	101.795	122.455	123.135

It can be seen from Table 1 that all five signals in CH1 are the time of real projectile signals, while there are seven signals in CH2, and there are two false signals. Based on the time of real projectile signals in CH1, the five real projectiles in CH2 can be combined into signals F11-F15, signals F12-F16, signals F13-F17, signals F11, F13-F16, signals F11, F14-F17 and signals F12, F14-F17 in CH2. Based on the time value of the five signal combinations of CH2, combined with the time value of the five signals of CH1, the correlation coefficients between the signal time of different combinations in CH2 and the time of five projectile signals in CH1 are calculated using Formula (12). The correlation coefficient results are shown in Table 2.

Table 2. The correlation coefficient results

Channel number and signal		CH2					
		F11-F15	F12-F16	F13-F17	F11、F13-F16	F11、F14-F17	F12、F14-F17
CH1	E11-E15	0.979288494	0.9999876	0.9729139	0.999571377	0.943376181	0.9475012

It can be seen from Table 2 that the correlation coefficient between signal F12-F16 in CH2 and signal E11-E15 in CH1 is the largest, so the time of each projectile passing through the LDS in the stop sensor is obtained according to the maximum correlation coefficients. Namely, the time of five real projectiles passing through two LDSs is determined. After calculation, the velocity of each projectile is obtained, as shown in Table 3. It can be found from Table 3 that these velocities also meet the velocity constraints of Formulas (10) and (11), which shows the feasibility and scientificity of the velocity constraint calculation model.

Table 3. The velocity data

Channel number and signal		Velocity(m/s)
CH1	CH2	
E11	F12	145.81
E12	F13	143.60
E13	F14	143.31
E14	F15	142.76
E15	F16	140.87

The analysis of the above tests and collected waveforms demonstrate that the output projectile signal voltage of the APDS decreases with the increase in the detection distance, indicating that the detection distance is farther and the laser reflected energy is smaller, which is in line with the law of laser emission characteristics. The detection ability of the APDS is better under low environmental illumination and it reflects the contribution of laser reflected energy in the detection process. Although the firing position is the same, the amplitude of each projectile signal is different because the attitude angle of the projectile is different in the flight process, and there is some change of $\cos\theta$ in the laser energy reflected by the surface of the projectile. The results are consistent with the model of Formula (4). In addition, if there is interference in the process of APDS detecting projectiles, the time extraction method of the modulus maximum projectile information based on wavelet change, the projectile velocity constraint criterion and the correlation coefficients can effectively reduce the influence of the interference signal.

7. Conclusions

Based on the velocity measurement principle of two APDSs, this paper studies the calculation method of laser reflection energy on the surface of the projectile in the LDS. The filter processing algorithm of the signal output by APDS and the time extraction algorithm of the moment when the projectile passes through the LDS are developed. Moreover, the double constraints of the time matching criterion and the correlation coefficient of the same projectile are provided. According to the design parameters of the APDS, the single shot and continuous shot tests are carried out under low environmental illumination to verify the effectiveness of the proposed algorithms. Combined with the agreed criteria of projectile velocity and the maximum correlation coefficient, the influence of false projectile signals can be effectively eliminated, and the effective projectile velocity data can be obtained. The work in this paper can provide a new method for the velocity measurement of warhead fragment formed by the projectile proximity explosion of ammunition weapons.

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