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Pulse compression-based improvement on the estimation accuracy of time interval between two trigger signals in light screen array

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ABSTRACT

This paper presents a novel method based on pulse compression theory to improve the detection accuracy of light screen array. According to the work principle of light screen array, discusses several important factors led to the deterioration of estimation accuracy of time interval between two trigger signals. Then, the estimation accuracy of time interval can be improved using two techniques (spread spectrum and matched filtering) in term of Cramer-Rao lower bound criterion. Combining with the two techniques, proposes a pulse compression-based algorithm to estimate the time interval between trigger signals accurately. Through simulation and analysis, the results show that the estimation accuracy of time interval between trigger signals is up to 5 μs under the noise-signal ratio(SNR) of 0 dB and two screens thickness ratio of 5/6, and the proposed method is scientific and feasible.

1. Introduction

Light screen array is a passive photoelectric instrument widely utilized in the measurement of barrel weapon such as pistol, rifle, machine gun. Unlike the previous sky screen velocity measurement device [1], besides the velocity of flying projectile, the light screen array can provide more measurement parameters, including coordinate, stance, and firing dispersion. This instrument mainly consists of four or six photo flux detectors (also known as light screen detector), data acquisition module, data and signal processing module [2–5]. These light screen detectors can correspondingly output trigger signals as soon as a projectile passing through their detection space (light screen). Next, these trigger signals are transmitted into the data acquisition module to realize signal sampling. Finally, the signal processing module makes use of these sampled datum to estimate the time interval between the trigger signals. Combining with the space geometry relationship between light screens, these time interval values are used to calculate the above measurement parameters according to some formulas, as it is described in detail in [2–5]. Therefore, the estimation accuracy of time interval between trigger signals mainly determines the detection accuracy of the instrument.

So far, several methods have been proposed in this field. NI and TIAN put forward an approach of −3 dB amplitude along drop edge and a generalized correlation method. The former method can be only used under high SNR condition, but the latter method has good noise immunity [6] and [7]. TIAN et al. presented a modified time acquisition method of projectile passing through a screen at a certain angle, but this method is only suitable for applying in laboratory [8]. LI and LEI adopted a

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wavelet transform modulus maximum detection to obtain the mutation positions in trigger signal, these mutation positions can be used to estimate the time interval, but it is invalid to estimate the time interval between the two trigger signals with different pulse width [9]. Thus, only the generalized correlation method is available in practice. However, the estimation accuracy of this method is also affected a little when two trigger signals have some difference in their pulse width [2] and [3].

In this paper, a novel method based on pulse compression theory is proposed to enhance the estimation accuracy of time interval between two trigger signals in light screen array. The main influence factors of estimation performance are discussed systematically. Two trigger signals are both compressed into two signals with spike feature using these two methods (spectrum spreading and matched filtering), so that these signals can be estimated their time interval accurately. Through simulation and analysis under two different conditions, the simulation prove that the estimation accuracy of time interval between trigger signals is 5 μs under the poor conditions, and the method also meet the performance requirement of light screen array.

2. Methods

2.1. The influence factors

Every trigger signal has some different features, such as pulse width, amplitude, rise time and fall time, so that its time interval is estimated difficultly. Through analysis in [2–5], it is found that the main reasons are electrical characteristics of detector, sky background noise, combined action of projectile length and screen thickness [3–8]. Since the electrical characteristics of detector are usually adjusted to realize uniformity, their influence can be neglected. Besides, the SNR of trigger signal becomes poor due to the influence of sky background noise, and the pulse width of trigger signal is determined by their projectile length l and the screen thickness [10].

The time interval between two trigger signals can be also considered as a difference between their signal time of arrival (TOA). In [12] and [13], there is an important appraisal criterion about the estimation accuracy of signal TOA. This appraisal criterion is Cramer-Rao lower bound (CRLB) of signal TOA maximum likelihood estimator can be expressed as

$$\varepsilon^2_{\hat{\tau}_{ml}} \geq \frac{1}{\frac{2E_s}{N_o}\beta^2} \tag{1}$$

where $\varepsilon^2_{\hat{\tau}_{ml}}$ is the mean square error of signal TOA estimator, E_s/N_o is SNR, β is the mean square root (MSR) bandwidth of signal. Approximately, β is deemed as the bandwidth (BW).

As can be seen from Eq. (1), the wider the signal BW is, the higher the estimation accuracy of signal TOA is; likewise, the higher the signal SNR is, the higher the estimation accuracy of signal TOA is. More precisely, BW and SNR are both influence factors which have the effect on the estimation accuracy of signal TOA. Accordingly, there are two requirements to improve the estimation accuracy of time interval between trigger signals as follows: spread spectrum and improvement on SNR. We will present an estimation method based on pulse compression theory systematically in the following section.

2.2. Related work

As is known to all, radar can be used to measure the precision distance between two objects. Its precision ranging function can be performed due to estimating the difference between the TOA of their two echoes. A pulse compression technique can transform pulse signals with large time-band width product into the corresponding pulses with ultra-narrow spike. These signals similar to the ideal impulse with ultra-wide bandwidth (or ultra-narrow pulse width) and noise-free (or ultra-high SNR) can be estimated their time interval accurately. Therefore, the pulse compression technique is widely applied to improve the range resolution as well as SNR in radar. Analogous to the pulse compression technique, the propose method also involves two main operations as follows: spread spectrum and matched filtering (improvement on SNR).

2.2.1. Spread spectrum

As it is mentioned in [14,15], the spectrum of signal can be spread by some techniques, such as sequence spread spectrum (DSSS), frequency-hopping spread spectrum (FHSS), time hopping spread spectrum (FHSS), linear frequency modulation (LFM). By comparison of other techniques, LFM signal can produce a large correlation effect [16]. Therefore, the LFM technique is adopted in this study.

The spread spectrum procedure of trigger signal based on LFM technique is represented in following steps:

Step-1: A wavelet transform modulus maximum detection is applied to detect the inflection points between the trigger signal and sky background noise [9,17]. Fig. 1 depicts the sampling signal of a light screen detector. In Fig. 4 from instant of time t_1 (start time), projectile nose starts to pierce the light screen; likewise, projectile base start to leave the light screen at the instant of time t_2 (cut-off time). That is to say, t_1 and t_2 are two inflection points in the sampling signal. Thus, the duration τ of trigger signal is the difference between t_1 and t_2. Finally, a trigger signal is extracted from sky background noise. Let $s_1(t)$ and $s_2(t)$ denote the trigger signal 1 and 2, respectively.