Similarity identification of characteristic curves of environment stimulus for fuze safety system

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Abstract. For the current problems of limited environmental information, weak environment stimulus, and difficult to distinguish from interference environment stimulus faced by low-rotation munition fuzes in arming, this paper proposes a similarity identification method for characteristic curves of environment stimulus based on Euclidean distance (ED), and corresponding similarity index. By judging the similarity between real-time speed curve and standard curve, abnormal curve and standard curve respectively, the reasonableness and reliability of similarity index and the feasibility of using it as the predetermined condition for fuze arming are confirmed.

Keyword: fuze safety system; environment stimulus; curve similarity identification.

1. Introduction

With the complex changes in the battlefield situation and the development of science and technology, weapons and equipment have put forward higher requirements for the environmental sensitivity of the fuze safety system. The fuze safety system generally uses recoil and centrifugal force as environment stimuli to arming the first and second safety respectively, but under weak environmental conditions, for example, low overload, non-spinning munitions such as mortar shells, rockets, recoilless shells, low-speed rotating munitions such as end-guided munitions, the centrifugal force during ballistic flight is very weak, and it is difficult to use mechanical safety features to convert the energy into the power to arming the fuze. As a result, the current low-rotation munition fuzes face the problems of limited environmental information, weak environment stimulus, and difficulty in distinguishing from the interference environment stimulus during the arming.

To solve the above problems, many scholars have conducted researches on how to use weak environment stimulus or perceive other new environment stimulus to arming the second safety. Bing Lv et al. designed a parallel two-degree-of-freedom (two-DOF) setback arming mechanism according to acceleration signal characteristics of weak launch and service conditions, and a model of an inertia switch with a low g-feature to be used in the electromechanical fuze of the proposed mechanism[1]. Hengzhen Feng et al. designed a low-voltage driven MEMS solid-state insurance for low firing overload, non-spinning munitions, and two independent insurance designs through corona discharge effect and energy storage capacitor discharge[2]. Yanning Gui et al. proposed a new method measuring the velocity of projectile flying in long range by using a small hole on the side wall of the fuzee, and developed a set of compact system on board corresponding to this new method, which can be installed in a standard size fuze and can be used to acquire ballistic features of projectile flight velocity for fuze safety system as one of environmental forces[3]. In the above research, the fuze safety system mostly adopts new mechanical safety features to use weak environment stimulus to arming. Based on the research of Gui, this paper proposes a new identification method of environment stimulus.

The end-guided munitions have some similarity between their ballistic flight curves without considering the end corrections, and thus, the similarity identification method of the characteristic curve can be used to identify the weak environment stimulus. The fuze can obtain some signals from the sensors, such as the acceleration change curve form the acceleration sensor, and the angle and velocity corresponding change curves from the gyroscope. Determine whether the projectile is in normal flight by judging the similarity between the measured and the standard characteristic curves of environment stimulus, and if the similarity indexes meet the predetermined conditions within the specified time windows, the arming signal can be output.

2. Theory and Methodology

The curve similarity identification methods can be classified as point-based, shape-based, segment-based and task-specific methods according to the principles. The ED method is point-based, and its advantages are linear computation time, computational simplicity, and applicability to discrete data. In this paper, the ED method is used for the similarity identification between the characteristic curves corresponding to the environment stimulus perceived during the projectile flight and the standard curves.

2.1 Euclidean Distance (ED)

The definition of ED is the average of the distance between the corresponding points of two curves, from which it can be seen that the ED calculation requires that the length of the curves must be the same, and its calculation formula is shown in Equation (1).

$$D_E(L_i, L_j) = \frac{1}{n}\sum_{k=1}^{n}\sqrt{\sum_{m=1}^{p}(a_k^m - b_k^m)^2} \tag{1}$$

Where D_E is the ED, a_k^m and b_k^m denote the coordinates of the m-th dimension on two p-dimensional curves L_i, L_j of length n respectively[4].

2.2 Additional Conditions

Due to the time series characteristic of the environment stimulus curves perceived during the projectile flight, and the ED method has certain shortcomings in measuring the similarity of time series, one is that the similarity of shape or change trend cannot be discerned when judging based on distance only; second is that the ED calculation needs to keep the data equal in length when measuring the similarity of curves[5]. This also means to keep the time alignment of the two curves. In order to solve these two problems, it is necessary to identify the similarity based on the characteristics of the curves themselves.

2.2.1 Trend of Curve Change.

In order to solve the problem that the ED method cannot identify the shape or change trend when judging based on distance only, using multiple time windows for testing as the judging additional condition is proposed.

2.2.2 Time Alignment.

The ED for similarity identification should ensure that the lengths of the two curves are aligned. Considering the time series characteristic of the projectile environment stimulus curves, the temporal alignment of the test curves with the standard curves should be ensured. Considering the consistency of environment sensitive devices and signal processing devices for the same type of projectile, and the consistent signal sampling frequency, the time alignment algorithm can be used as the judging additional condition to align the time of the test curves with the standard curves within the test time window.

2.3 Methodology

The similarity identification methodology of characteristic curves of environment stimulus based on ED is shown as below.

2.3.1 Establishing standard environmental stimulus curves.

According to the projectile design, flight motion law and measured data, the ballistic curve set of the projectile in normal flight is constructed, which can be classified on the basis of different characteristics, such as overload curves, speed curves and velocity curves. The ballistic curve set is individually time-aligned according to the classification, and the mean value of the corresponding environment stimulus signal at each time point is obtained to construct the standard environment stimulus curve, and the upper and lower (U&L) boundary values corresponding to each time point are determined as the basis for the subsequent establishment of a standard pipeline. The calculation process is shown in Equation (2)~(4).

$$[P_t]_s = \frac{1}{m}\sum_{k=1}^{m}[(P_n^k)_t] \ \ ,k \in [1,m] \tag{2}$$

$$[P_t]_{up} = Max[(P_n^k)_t] \ \ ,k \in [1,m] \tag{3}$$

$$[P_t]_{down} = Min[(P_n^k)_t] \ \ ,k \in [1,m] \tag{4}$$

Where $[P_t]_s$ is the mean value of the ballistic curve set composed of m curves at time t, $(P_n^k)_t$ is the value of the n-th dimensional curve vector of the k-th curve at time t, and $[P_t]_{up}$ and $[P_t]_{down}$ are the maximum and minimum values of the ballistic curve set at time t, respectively.

2.3.2 Building a standard pipeline based on ED method.

The U&L boundaries of the environment stimulus curve corresponding to each point (a total of N points) in the test time window ($t \in [T_s, T_e]$) are operated with the standard curve for the differences, which are averaged separately to obtain the corresponding U&L translations (ΔL_1 and ΔL_2) in the test time window. After standard curve translations, the U&L boundaries of the standard pipeline based on the same reference points are obtained. The calculation process is shown in Equation (5)~(8).

$$\Delta L_1 = \frac{1}{N}\sum_{t=T_s}^{T_e}([P_t]_s \text{-} [P_t]_{up}) \ \ ,t \in [T_s, T_e] \tag{5}$$

$$\Delta L_2 = \frac{1}{N}\sum_{t=T_s}^{T_e}([P_t]_s - [P_t]_{down}) \ \ ,t \in [T_s, T_e] \tag{6}$$

$$[B_t]_{up} = [P_t]_s - \Delta L_1 \ \ ,t \in [T_s, T_e] \tag{7}$$

$$[B_t]_{down} = [P_t]_s \text{-} \Delta L_2 \ ,t \in [T_s, T_e] \tag{8}$$

Where $[B_t]_{up}$ and $[B_t]_{down}$ are the U&L boundaries of the standard pipeline after translations, and N is the total number of sample points within the time window $[T_s, T_e]$.

2.3.3 Establishing a benchmark for curve similarity identification based on ED method.

At each time point within the test time window, the U&L boundaries of the standard pipeline are differenced from the standard curve, respectively, to obtain the corresponding U&L boundary EDs, which are normalized - the ratio of which to the absolute value of the corresponding standard curve at that time point is calculated to obtain the benchmark for judging the U&L boundary EDs of the standard pipeline within this time window. The calculation process is shown in Equation (9), (10).

$$D_E([P_t]_s, [B_t]_{up}) = \frac{[B_t]_{up} - [P_t]_s}{[P_t]_s} \ \ ,t \in [T_s, T_e] \tag{9}$$

$$D_E([P_t]_s, [B_t]_{down}) = \frac{[P_t]_s - [B_t]_{down}}{[P_t]_s} \ \ ,t \in [T_s, T_e] \tag{10}$$

Where $D_E([P_t]_s,[B_t]_{up})$ and $D_E([P_t]_s,[B_t]_{down})$ are the normalized EDs between the U&L boundaries of the standard pipeline and the standard curve at time t, respectively.

2.3.4 Measured environment stimulus curve processing.

The measured environment stimulus curve and the standard curve are aligned in time, and the difference between the real-time curve and the standard curve at each time point within the test time window is averaged to obtain the translation (ΔL). Then, the translation of the real-time curve relative to the standard curve is completed. The calculation process is shown in Equation(11), (12).

$$\Delta L = \frac{1}{N}\sum_{t=T_s}^{T_e}([C_t]-[P_t]_s) \quad ,t \in [T_s,T_e] \tag{11}$$

$$[C_t]_s = C_t - \Delta L \ \ ,t \in [T_s,T_e] \tag{12}$$

Where C_t is the corresponding value of the measured curve at time t and $[C_t]_s$ is the measured curve after translation.

2.3.5 Calculate the ED of the measured curve.

The ED between the measured curve after translation and the standard curve corresponding to each time point within the test time window is calculated and normalized - the ratio of the ED to the absolute value of the corresponding standard curve at that time point.

$$D_E([C_t]_s,[P_t]_s) = \frac{\left|[C_t]_s - [P_t]_s\right|}{[P_t]_s} \ \ ,t \in [T_s,T_e] \tag{13}$$

Where $D_E([C_t]_s,[P_t]_s)$ is the normalized ED between the measured curve after translation and the standard curve.

2.3.6 Similarity identification.

When the normalized ED ($D_E([C_t]_s,[P_t]_s)$)between the measured curve after translation and the standard curve is within the normalized EDs ($D_E([P_t]_s,[B_t]_{up})$ and $D_E([P_t]_s,[B_t]_{down})$) between the U&L boundaries of the standard pipeline and the standard curve, this point is judged to satisfy the requirement, and the set of all points within the test time window that satisfy the identification rule is thus obtained. The identification conditions are shown in Equation (14).

$$\sum C_D = \begin{cases} \sum (D_E([C_t]_s,[P_t]_s) \le D_E([P_t]_s,[B_t]_{up})) & ,[C_t]_s \ge [P_t]_s, t \in [T_s,T_e] \\ \sum (D_E([C_t]_s,[P_t]_s) \le D_E([P_t]_s,[B_t]_{\mathrm{down}})) & ,[C_t]_s \le [P_t]_s, t \in [T_s,T_e] \end{cases} \tag{14}$$

Where $\sum C_D$ is the number of characteristic points that satisfy the identification rule.

Accordingly, similarity index can be identified as Equation (15) shown.

$$\lambda_1 = \frac{\sum C_D}{N} \tag{15}$$

Where λ_1 is the similarity index that satisfies the identification rule. When multiple time windows are used for test, multiple similarity indexes are obtained, and finally, whether this curve is in normal flight status is judged by determining whether the magnitude of the indexes of the real-time curve meets the predetermined conditions, and if all meet the predetermined conditions, take actions to arming.

The Similarity Identification Methodology of characteristic curves of environment stimulus based on ED is shown in Figure 1.

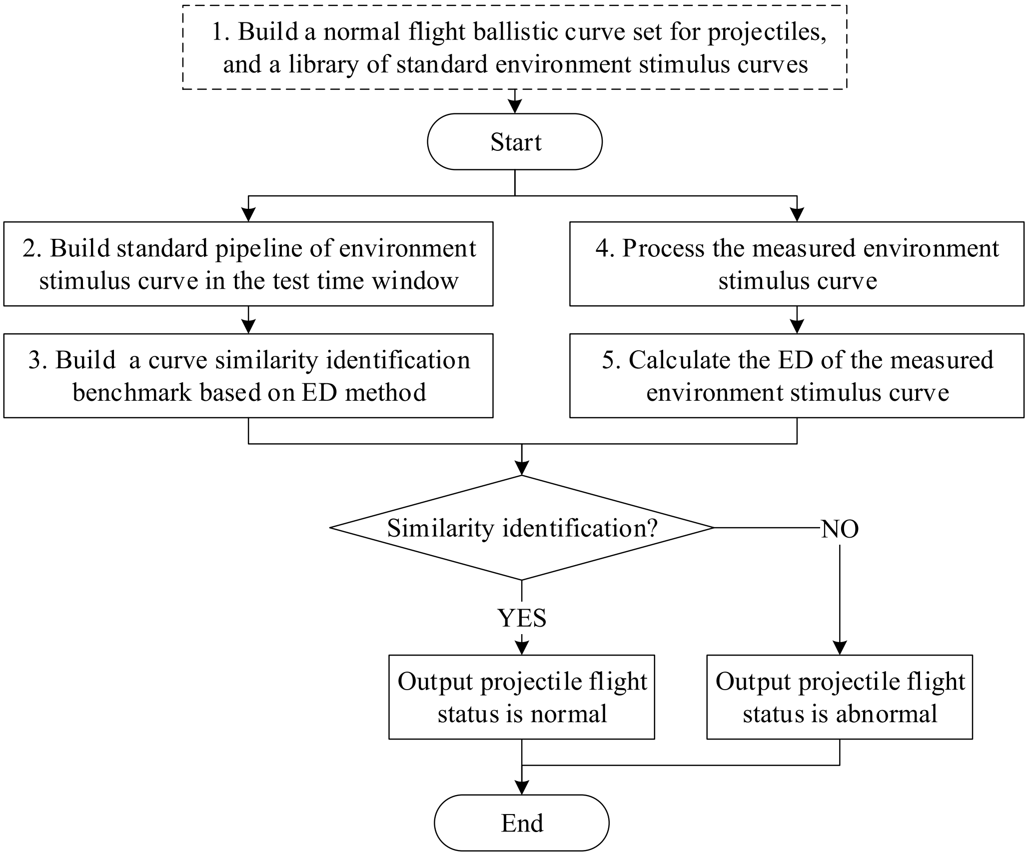

Figure 1. Similarity Identification Methodology of characteristic curves based on ED.

3. Algorithm Implementation

The algorithm is programmed based on Matlab. Firstly, the external ballistic model is established according to the motion law of the uncontrolled section of Terminal Correction Mortar (TCM), and then the designed normal ballistic flight set of the projectile is obtained, after that, the standard velocity curve of the projectile flight speed is established according to Equation (2)~(4). Then, the seven sets of measured velocity curves are used to verify the correctness of the algorithm corresponding to the Methodology. After completing the time alignment of the measured environment stimulus curves and the standard curves, the EDs within the corresponding time windows are calculated separately, and finally judge whether the EDs within multiple time windows satisfy the predetermined conditions and outputs the similarity index results. In addition, the simulation of abnormal flight conditions is carried out to verify the reliability of the algorithm.

3.1 External ballistic simulation of TCM

The external ballistic simulation of the uncontrolled section of TCM is mainly to obtain the flight velocity of the projectile, thus the rotational speed of the projectile is ignored in this paper, and mass point ballistic model in right-angled coordinate system is used for calculation. According to the environment stimulus in the inertial force environment, the equation of motion can be obtained as shown in Equation (16)~(20).

$$\begin{cases} \dfrac{dv}{dt} = -CH(Y)F(V) - g\sin\theta \\ \dfrac{d\theta}{dt} = -\dfrac{g\sin\theta}{v} \\ \dfrac{dY}{dt} = \omega \\ \dfrac{dX}{dt} = u \end{cases} \tag{16}$$

$$u = v\cos\theta \tag{17}$$

$$\omega = v\sin\theta \tag{18}$$

$$H(Y) = e^{-\frac{1}{Rq}\int_0^y \frac{dY}{T}} \cdot \frac{T_{ON}}{\tau} \tag{19}$$

$$F(v) = 4.736\times10^{-4} v^2 C_{x_{ON}}(\frac{v}{c}) \tag{20}$$

The algorithm uses the fourth-order Runge-Kutta method with fixed step size for solving the external ballistic motion equations. The solution flow is shown in Figure 2.

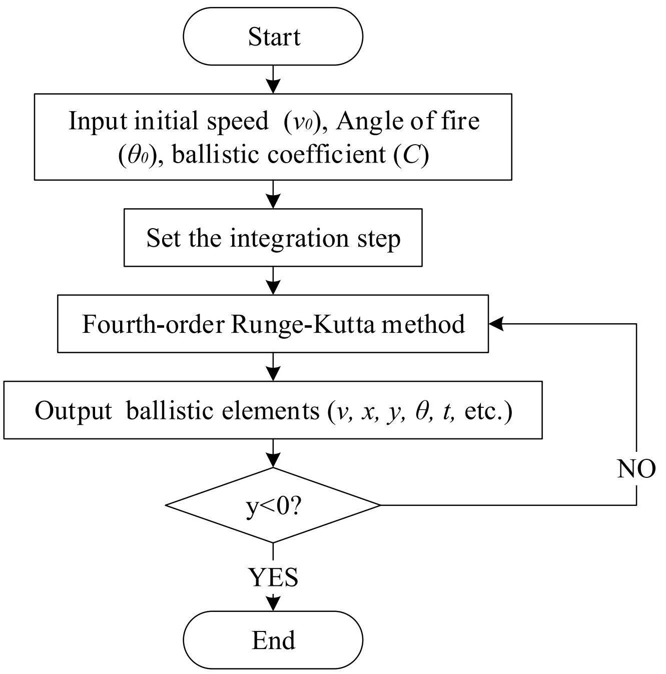

Figure 2. The external ballistic simulation algorithm.

3.2 Build speed curve set

Constructing the velocity curve set based on the external ballistic simulation of the uncontrolled section of TCM: setting the initial velocity (v_0) to 320~390m/s, the angle of fire (θ_0) to 56°, and the ballistic coefficient (C) calculated as 0.74, the following 8 sets of ballistic curves for the standard case are obtained according to the above simulation algorithm of external ballistic, as Figure 3 shown.

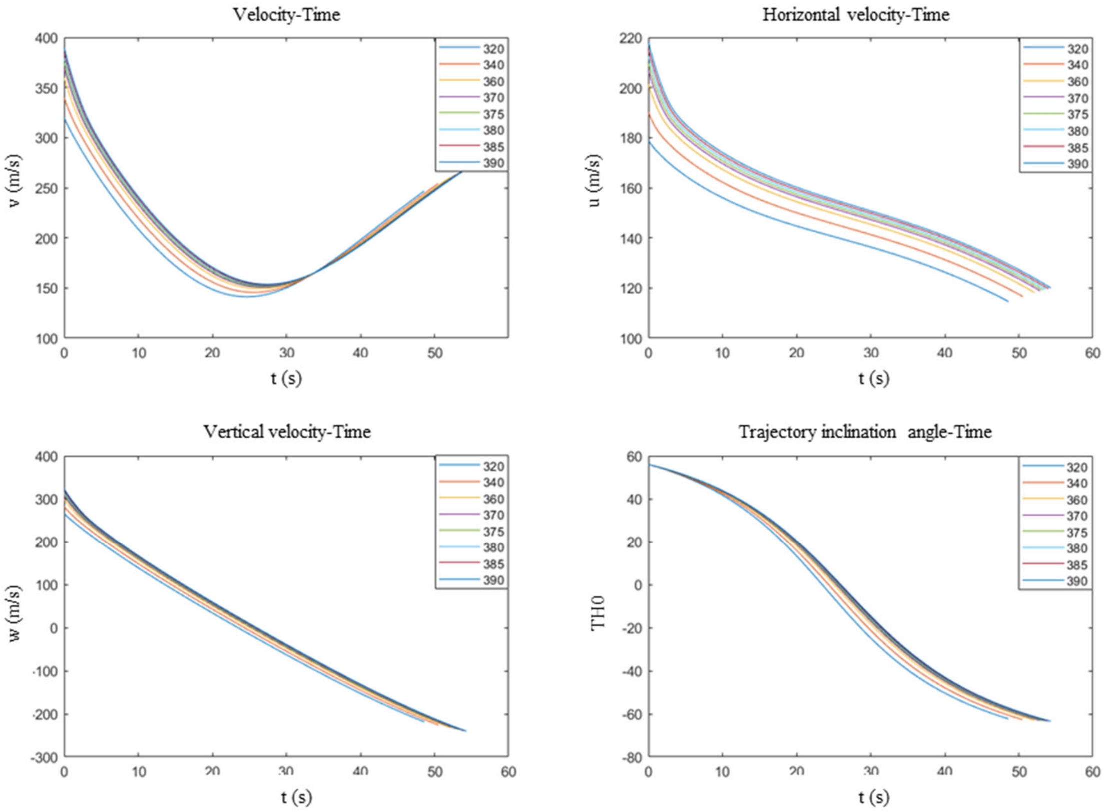

Figure 3. External ballistic simulation curve set at different initial velocities (θ_0 = 56°).

3.3 Real-time curve of TCM

The seven velocity curves of TCM from #1 to #7 measured are shown in Figure 4.The enlarged graph between 30~40s is shown in Figure 5.

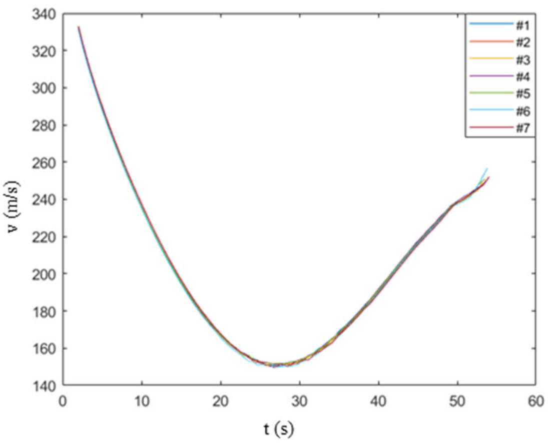

Figure 4. Measured velocity curve.

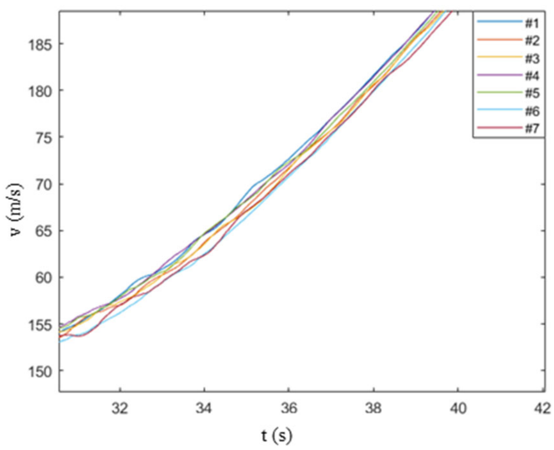

Figure 5. Measured velocity curve (30~40s).

3.4 Normal velocity curve similarity identification

The standard velocity curve and the U&L boundary curves (as shown in Figure 6) are constructed from the set of velocity curves obtained from the above external ballistic simulation (as shown in Figure 3). The real-time curve #1 (with 5106 sampling points) and the standard curve (with 489 sampling points) are shown in Figure 7, which are processed through time alignment as shown in Figure 8.

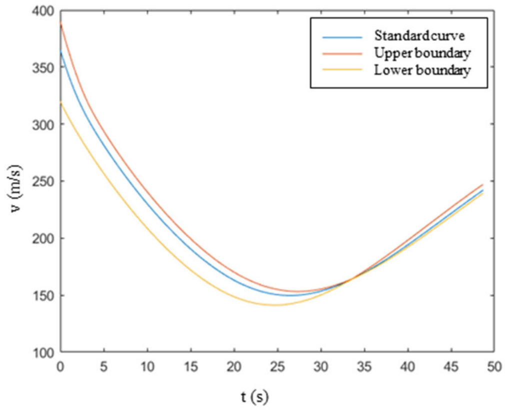

Figure 6. Standard velocity curve and U&L boundaries.

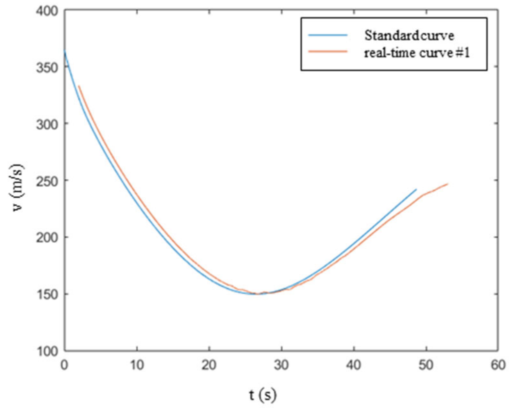

Figure 7. Standard velocity curve and real-time curve #1.

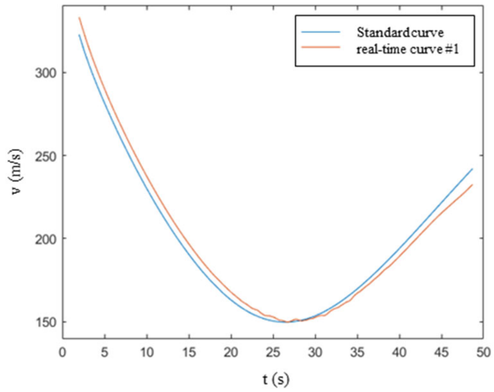

Figure 8. Standard velocity curve and real-time curve #1 (after time aligned).

According to the analysis of velocity curve characteristics, it is known that its curvature changes first large and then small, in order to ensure the similarity of the change trend of the real-time curve and the standard curve, multiple time windows can be used as an additional test condition. According to Figure 6, it can be seen that the standard velocity curve is very similar to the U&L boundary curves at around 34s, and in order to improve the accuracy of curve similarity identification, the similarity between the real-time curve and the standard curve should be observed before 34s. Therefore, three time windows of 5~10s, 15~20s and 22s~32s are used in this scheme to judge whether the ED of real-time curve #1 from the standard curve is less than the EDs of the U&L boundaries of the pipe, as Figure 9, Figure 10 and Figure 11 are shown, and the similar indexes (λ_1) are all equal to 1, which proves that the real-time curve #1 is in the normal flight state.

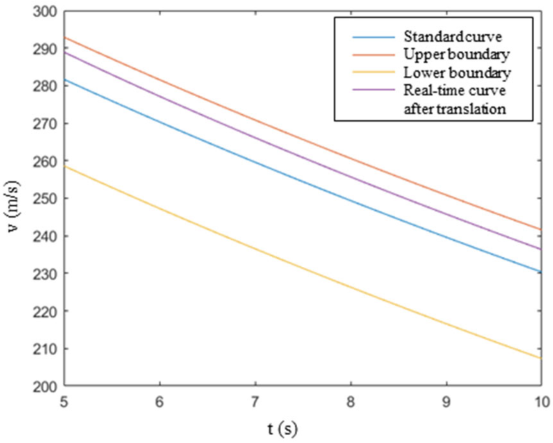

Figure 9. Standard velocity curve and real-time curve after translation (5~10s).

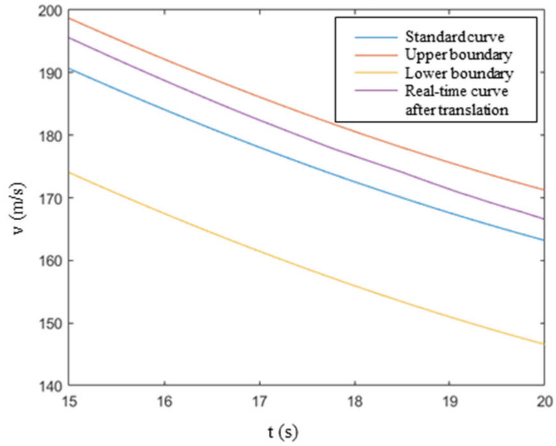

Figure 10. Standard velocity curve and real-time curve after translation (15~20s).

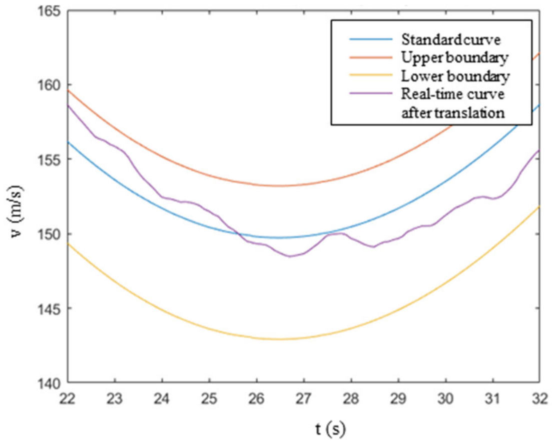

Figure 11. Standard velocity curve and real-time curve after translation (22~32s).

The other 6 real-time curves (#2~#7) identified by this identification method also have λ_1 of 1, which proves the correctness of the similarity identification method of environment stimulus curves based on ED.

3.5 Abnormal velocity curve similarity identification

To verify the reliability of the ED-based similarity identification method for environment stimulus curves, two types of abnormal curves (#8 and #9) are simulated. The #8 curve after time alignment is shown in Figure 12, and with the standard pipeline curves in the three time windows of 5~10s, 15~20s and 22~32s are shown in Figure 13~15, and λ_1 calculated are equal to 0, 0 and 0.0980, respectively. The #9 curve after time alignment is shown in Figure 16 and with the standard pipeline curves in the three time windows of 5~10s, 15~20s and 22~32s are shown in Figure 17~19, and λ_1 calculated are equal to 0, 0.1373 and 0, respectively. From the values of λ_1, we can see that curves #8 and #9 are abnormal curves and cannot output the arming signal.

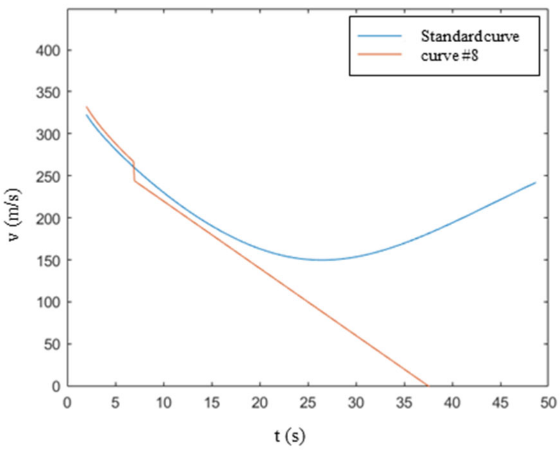

Figure 12. Standard velocity curve and curve #8 (after time alignment).

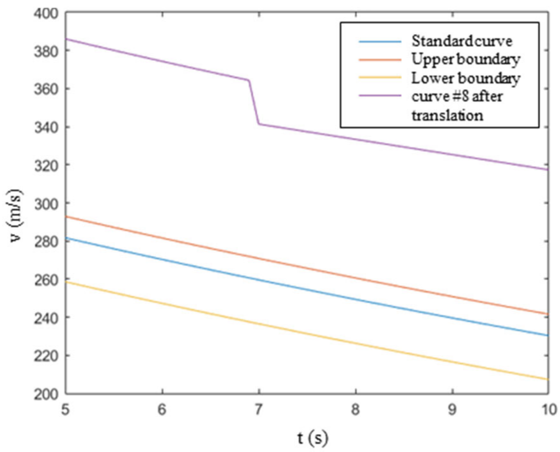

Figure 13. Standard pipeline and curve #8 after translation (5~10s).

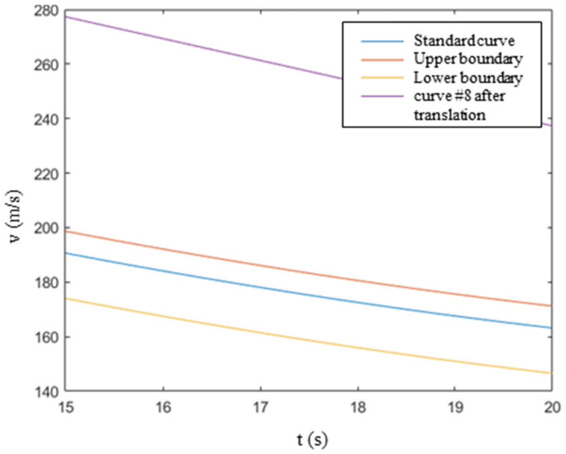

Figure 14. Standard pipeline and curve #8 after translation (15~20s).

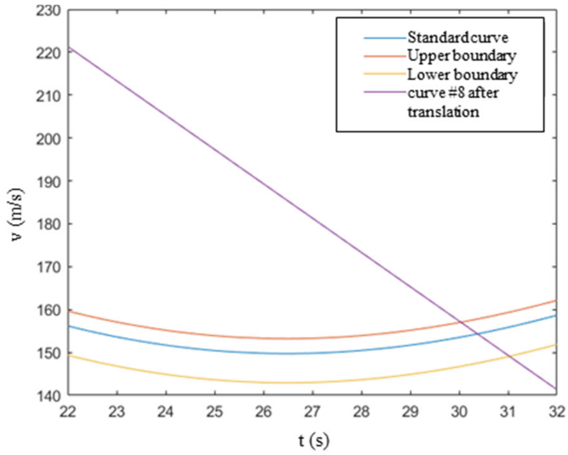

Figure 15. Standard pipeline and curve #8 after translation (22~32s).

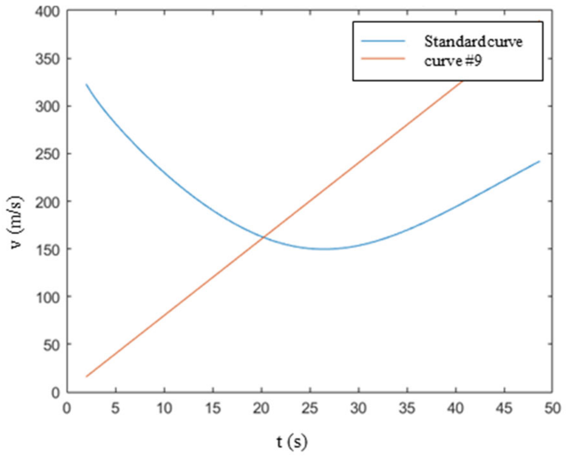

Figure 16. Standard velocity curve and curve #9 (after time alignment).

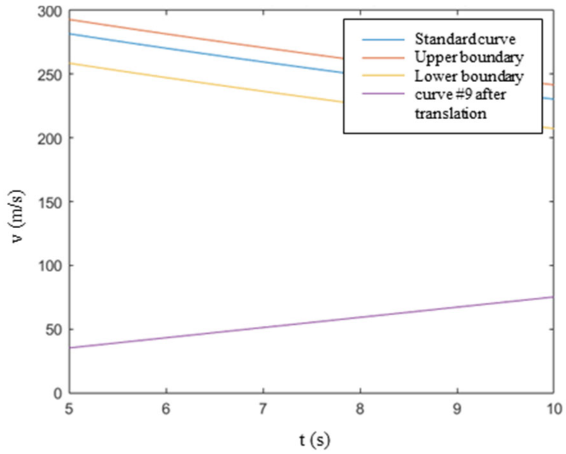

Figure 17. Standard pipeline and curve #9 after translation (5~10s).

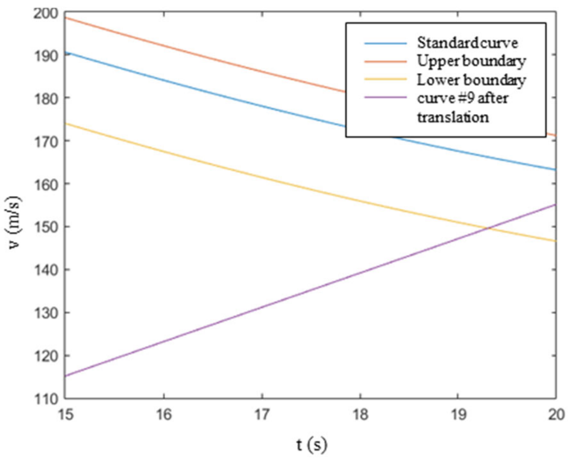

Figure 18. Standard pipeline and curve #9 after translation (15~20s).

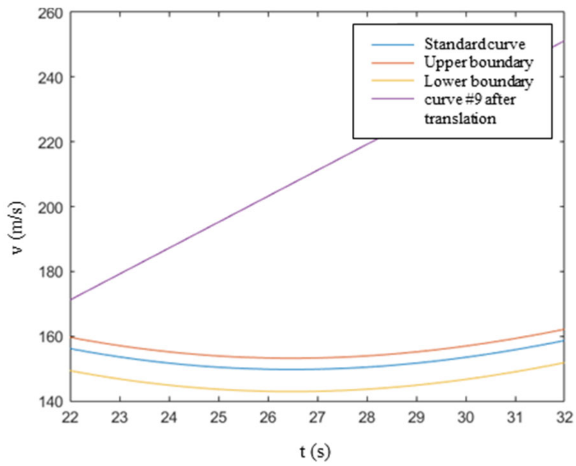

Figure 19. Standard pipeline and curve #9 after translation (22~32s).

From the above analysis, it can be determined that λ_1 of the normal speed curve are all close to 1, while λ_1 of the abnormal speed curve are much less than 1. Therefore, the values of λ_1 can be used as the predetermined condition for fuze arming with certain reliability.

4. Conclusions

This paper proposes a similarity identification method of characteristic curves of environment stimulus for fuze safety system based on ED, which is different from the traditional threshold-based environment stimulus quantity feature identification method. The feasibility and reliability of the method and the corresponding similarity index as a predetermined condition for fuze arming are confirmed by judging the curve similarity between the real-time velocity curve and the standard curve, the abnormal curve and the standard curve. Taking the velocity curve of TCM as an example, the ED-based curve similarity index is identified under the condition that multiple ED similarity indexes (λ_1) are close to 1. In practical application, the predetermined similarity index threshold (λ_1 = 0.8) can be adjusted according to the actual situation, and when the calculated λ_1 is greater than this threshold, the projectile can be judged to be in a normal flight state and the arming signal can be output for release the insurance.

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