doi:10.3788/gzxb20164505.0514003

脉冲激光周向探测最佳定向起爆技术

徐孝彬,张合
(南京理工大学 智能弹药技术国防重点学科实验室,南京 210094)

摘　要:根据常规弹药最佳定向起爆要求,针对弹目交会环境,建立脉冲激光周向探测系统单次和二次扫描最佳起爆延时模型和最佳起爆方位角模型.运用 Matlab 对模型参量进行数值仿真,分析探测方位角、弹目间距和目标俯仰角对最佳起爆延时和起爆方位角的影响.结果表明:当激光扫描到单次目标时,最佳起爆延时随弹目之间距离的增大而增大,随探测方位角的增大先减小后增大,最佳起爆延时的变化范围在 0～20 ms 之间;当脉冲激光周向探测系统扫描到二次目标时,在大部分时间内最佳起爆延时时间为 0 ms;在非零区域内,最佳起爆延时随弹目之间距离的增大而增大,随探测方位角的增大先变大后变小.

关键词:定向战斗部;脉冲激光周向探测;最佳起爆延时;最佳起爆方位角;最佳起爆策略
中图分类号:TJ43　　**文献标识码**:A　　**文章编号**:1004-4213(2016)05-0514003-6

Optimum Directional Detonating Technology of Pulsed Laser Circumferential Detection

XU Xiao-bin, ZHANG He
(*ZNDY of Ministerial Key Laboratory, Nanjing University of Science and Technology, Nanjing* 210094, *China*)

Abstract: According to the requirements of the optimum directional detonating of conventional ammunition, the models of optimum detonating delay time and optimum detonating azimuth were established for single and double scan of the pulse laser circumferential detection system. Matlab is used to simulate the parameters of the model. The influence of detection azimuth, missile-target distance and target pitch angle on the optimum delay time and the detonating azimuth was analyzed. When the laser circumferential detection system scans a target once, the optimal initiation time increase withs the increasing of the missile-target distance, and then increases with the increasing of the azimuth. The change range of the optimal initiating delay is between 0 ms and 20 ms. When the pulse laser circumferential detection system scans target twice, the optimal initiation delay time is 0 ms in most of the time. In the non-zero region, the optimal initiation delay increases with the increasing of missile-target distance.

Key words: Aimed warhead; Pulsed laser circumferential detection; Optimum detonating delay time; Optimum detonating azimuth; Optimum detonating strategy
OCIS Codes: 140.0140; 140.3538; 140.346

0 Introduction

The best detonating technology of aimed warhead is the prerequisite to make full use of execution of warhead in order to improve the lethality of conventional ammunition and the efficiency of fuze-warhead coordination. Pulsed laser circumferential detection is a mechanism with a pulsed laser beam

---

Foundation item: The Weapon-equipment Pr-research Project Foundation (No. 51305020104)

First author: XU Xiao-bin (1990—), male, Ph.D. degree, mainly focuses on laser detection and target recognition. Email:njustxxb@163.com

Responsible author(Corresponding author): ZHANG He (1957—), male, professor, Ph.D. degree, mainly focuses on laser detection and target recognition. Email:hezhang@mail.njust.edu.cn

Received: Dec. 23, 2015; **Accepted**: Feb. 26, 2016

sweeping 360° which could actively detect the target near the shell. A large number of researches have been carried out at home and abroad about the pulse laser circumferential detection. The parameter measurement of optical transmitter by XIE Jing[1] was studied. GAN Lin designed pulse laser driving power and laser receiving system[2-3]. STEINVALL studied on the characteristics of pulse laser echo[4-5]. Moreover, the distance and azimuth information are provided for detonation of aimed warhead. Therefore, it is significant to establish denotation models and azimuth models of directional warhead at time of missile-target encounter for application of best detonating technology[6].

It is concluded that optimum detonating delay increases with the increasing in missile-target distance by ZHU Jing-wei and ZHUANG Zhi-hong, etc, in regard optimal denotation problem[7-8]. These conclusions are based on the air-to-air missile[9-10]. However, relative angles and velocity of missile-target could not be obtained in conventional ammunition. Therefore, this kind of model could not be applied to detect in conventional ammunition. The optimum detonating delay model of the six beam pulsed laser detections for the directional warhead by GUO Ze-rong[11] is based on a certain speed of rotation which is inapplicable to non-rotating ammunition. The optimum detonating delay model of two dimensional pulsed laser established by ZHANG Xiang-jin[12] is not applied to all cases of missile-target encounter.

In this paper, optimum detonating delay model and optimum detonating azimuth model are established by using of the parameters obtained from the laser circumferential detection system. Numerical simulation analysis is carried out, and then optimum detonating strategy for the laser circumferential detection is proposed.

1 Operational principle

The operational principle of pulsed laser circumferential detection system: the power supply system starts to operate after the launching projectile. Periodic pulse signal is generated to illumine laser diode after time-delay. Laser beam incidents on the whole anti plane mirror through collimating lens. With the high speed of the reflected mirror, the reflected beam is transmitted in the air through a transparent window, and turns into a diffuser reflection beam when meets the target. The diffuse reflection laser beam is reflected from the receiving mirror to the laser receiving focusing lens. The beam is gathered in the photoelectric detector. Laser echo signal is acquired. Then the distance between system and targets could be calculated by signal processing. Meanwhile the speed of motor is calculated from the output signal of the azimuth detection module. Azimuth is calculated by processing the echo signal. Working principle of the pulsed laser circumferential detection system is shown in Fig. 1.

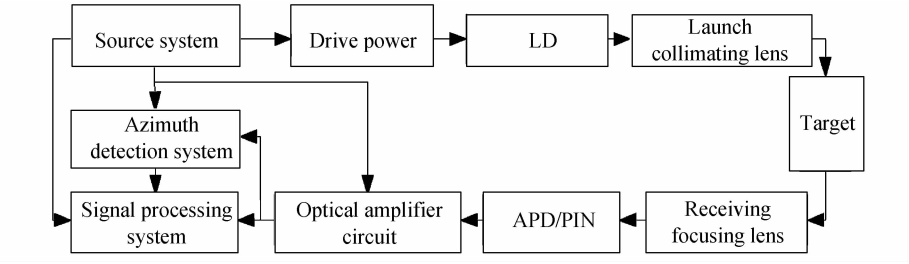


Fig. 1 Principle block diagram of pulsed laser circumferential detecting system

2 Optimum detonating model establishment

2.1 Establishment of coordinate system

In order to study the optimum initiation model of the pulsed laser circumferential detection system, three kinds of coordinate systems are established. They are ground coordinate system, missile coordinate system and target coordinate systems which are shown in Fig. 2.

Coordinate transformation between missiles coordinate system and target coordinate system is Shown below

$$[x_1 \quad y_1 \quad z_1]^{\mathrm{T}} = A_{1N} A_{2N}^{t} [x_2 \quad y_2 \quad z_2]^{\mathrm{T}} \tag{1}$$

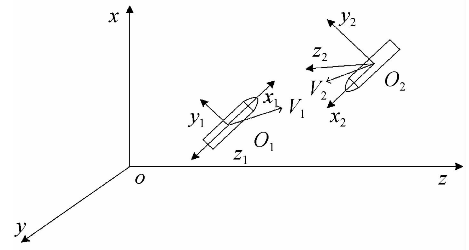


Fig. 2 Missile target intersection coordinate system

$$\boldsymbol{A}_{1N} = \begin{bmatrix} \cos\theta_1\cos\psi_1 & \sin\theta_1 & -\cos\theta_1\sin\psi_1 \\ -\sin\theta_1\cos\psi_1 & \cos\theta_1 & \sin\theta_1\sin\psi_1 \\ \sin\psi_1 & 0 & \cos\psi_1 \end{bmatrix}$$

$$\boldsymbol{A}_{2N}=\begin{bmatrix} \cos\theta_2\cos\psi_2 & \sin\theta_2 & -\cos\theta_2\sin\psi_2 \\ -\sin\theta_2\cos\psi_2 & \cos\theta_2 & \sin\theta_2\sin\psi_2 \\ \sin\psi_2 & 0 & \cos\psi_2 \end{bmatrix} \quad (2)$$

The yaw angle and pitch angle of the ground coordinate system are separately ψ_1 and θ_1 in the missile body coordinate system. Respectively, yaw angle and pitch angle of the target coordinate system relative to the ground coordinate system are ψ_2 and θ_2. The transformation matrix between missile coordinate system and ground coordinate system is $\boldsymbol{A}_{1N}$, and the transformation matrix between target coordinate system and ground coordinate system is $\boldsymbol{A}_{2N}$.

2.2 Optimum detonating model of missile-target encounter

When pulsed laser circumferential detection system detects an incoming target, the intersection time of projectile and target is short. Now we have the following assumptions: 1) The missile and target are making uniform linear motion. The direction and their respective longitudinal axes coincide. 2) Fragment keeps the constant velocity without considering attenuation in the air. 3) Vulnerability analysis is not considered for target. The key part of the target is in the geometric center. 4) We assume that the target is an elongated rod. The center of mass is in the center of the geometry. The total length is K. The uniform of it is meter.

When pulse laser circumferential detection system could scan the target only once, the missile-target intersection is shown in Fig. 3. A point is the projectile laser beam position. D point is the target geometry center of the laser beam. During the flight of the projectile along OX_1 axis in constant speed, Laser beam sweeps 360 degrees to actively detect the target near the shell. The target keeps uniform rectilinear motion along the axis of target with velocity V_2. The distance between missile and target for the laser detection is R_1. The angle between the direction of laser fuze and the velocity of the projectile is β. When system detects the target, the azimuth is α_1. The warhead is detonated after the time delay. The target is hit by fragment at the Q point. Optimum detonating azimuth is γ. Explosion fragment flights at the speed of V_0, axis is 90°. According to the assumption the projectile velocity is in coincidence with OX_1 of the missile coordinate system. The target velocity is in coincidence with OX_2 of the target coordinate system.

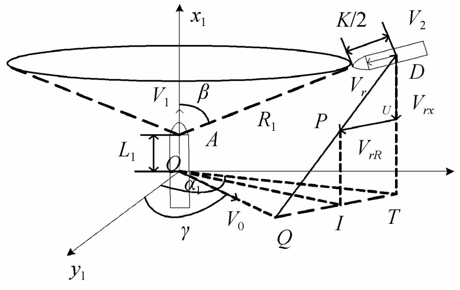


Fig. 3 Diagram of the single missile target intersection

According to Fig. 3, the velocity of the projectile is $(v_1, 0, 0)$ in the body coordinate system. The speed of the target is $(v_2, 0, 0)$ in the target coordinate system. Then the velocity of target in the body coordinate system is

$$V_2'=\boldsymbol{A}_{1N}\boldsymbol{A}_{2N}^{\mathrm{t}}\boldsymbol{V}_2^{\mathrm{t}}=[v_{2x} \quad v_{2y}]^{\mathrm{T}} \quad (3)$$

According to the transformation of coordinate system, the relative speed of the target in the missile body coordinate system is

$$\boldsymbol{V}_r=\boldsymbol{A}_{1N}\boldsymbol{A}_{2N}^{\mathrm{t}}\boldsymbol{V}_2^{\mathrm{t}}-\boldsymbol{V}_1^{\mathrm{t}}=[v_{rx} \quad v_{ry} \quad v_{rz}]^{\mathrm{T}} \quad (4)$$

The coordinate of D point is $(R_1\cos\beta+L_1+\frac{K}{2}\cdot\cos\theta_2'\cos\psi_2', R_1\sin\beta\cos\alpha_1-\frac{K}{2}\sin\theta_2', R_1\sin\beta\sin\alpha_1-\frac{K}{2}\cos\theta_2'\sin\psi'_2)$.

$$\begin{cases} \theta_2'=\arcsin\dfrac{v_{2y}}{\sqrt{v_{2x}^2+v_{2y}^2+v_{2z}^2}} \\ \psi_2{}'=-\arctan(v_{2z}/v_{2x}) \end{cases} \quad (5)$$

Pitch angle of target velocity is θ_2' in the missile coordinate system. Yaw angle of target velocity is ψ_2' in the missile coordinate system

The line DQ could be described as

$$\frac{x-x_D}{v_{rx}}=\frac{y-y_D}{v_{ry}}=\frac{z-z_D}{v_{rz}}=t \quad (6)$$

The Q point is in the plane of OZ_1Y_1. We put the function $x_Q=0$ in the Eq. (6).

$$x_D=-v_{rx}(\tau+t_1) \quad (7)$$

After initiation scattering distance of fragment is distance between fragment origin O point and meeting point P. We have

$$V_0 t_2=\sqrt{y_Q^2+z_Q^2} \quad (8)$$

Optimum detonating delay τ and optimum detonating azimuth γ can be calculated according to the Eqs. (7)~(9).

$$\tau=-\frac{V_0 x_D+\sqrt{(x_D v_{ry}-v_{rx}y_D)^2+(x_D v_{rz}-v_{rx}z_D)^2}}{v_{rx}V_0} \quad (9)$$

$$\gamma=\arctan\frac{x_D v_{rz}-v_{rx}z_D}{x_D v_{ry}-v_{rx}y_D} \quad (10)$$

When the pulse laser circumferential detection system could scan the target twice, the missile-target intersection is shown in Fig. 4. When the target detected for the first time, the distance between missile and target is R_1. The azimuth of target relative to missile is α_1. When the target is scanned for the second time after value of t_2, the distance between missile and target is R_2. The azimuth of target relative to missile is α_2. The warhead is detonated after the delay time. Fragment hits target at P point. Optimum detonating angle is γ. Based on parameters of two detections, the system can calculate in the real time. The initial delay and detonating azimuth can be accurately calculated.

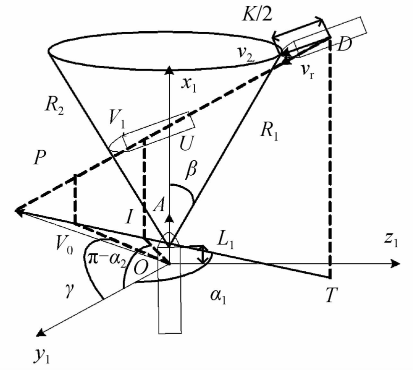


Fig. 4 Diagram of twice missile target intersection

When the target is detected second times, the motor speed is very high, the laser beam is still hit in the warhead, the U point coordinates are ($R_2\cos\beta+L_1+\frac{K}{2}\cos\theta_2'\cos\psi_2'$, $R_2\sin\beta\cos\alpha_2-\frac{K}{2}\sin\theta_2'$, $R_2\sin\beta\cdot\sin\alpha_2-\frac{K}{2}\cos\theta_2'\sin\psi_2'$).

Substitute coordinates of D and U point into Eq. (6). Relative speed can be acquired

$$v_r=\left(\frac{\cos\beta(R_2-R_1)}{t_1},\frac{\sin\beta(R_2\cos\alpha_2-R_1\cos\alpha_1)}{t_1},\frac{\sin\beta(R_2\sin\alpha_2-R_1\sin\alpha_1)}{t_1}\right)\tag{11}$$

The function of $x_Q=0$ is substituted into Eq. (6)

$$t_2+\tau+t_3=-\frac{t_2(R_1\cos\beta+L_1+K\cos\theta_2'\cos\psi_2'/2)}{\cos\beta(R_2-R_1)}\tag{12}$$

With Eqs. (4), (6), and (8) substituting into Eq. (12), we can get the optimum detonating delay and the optimum burst angle

$$\tau=-\frac{t_1(R_1\cos\beta+L_1+K\cos\theta'^2\cos\psi_2'/2)}{\cos\beta(R_2-R_1)}-\frac{\sqrt{(A-B)^2+(C-D)^2}}{V_0}-t_2\tag{13}$$

$$\gamma=\arctan\frac{C-D}{A-B}\tag{14}$$

where,

$$A=[\sin\beta(R_2\cos\alpha_2-R_1\cos\alpha_1)(R_1\cos\beta+L_1+K\cos\theta'_2\cos\psi'_2/2)]/t_2$$

$$B=[(R_1\sin\beta\cos\alpha_1-\frac{K}{2}\sin\theta'_2)(v_1t_2+\cos\beta(R_2-R_1))]/t_2$$

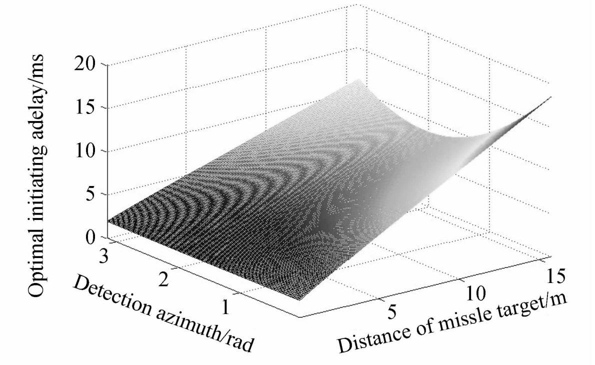
$$C=[\sin\beta(R_2\sin\alpha_2-R_1\sin\alpha_1)(R_1\cos\beta+L_1+K\cos\theta'_2\cos\psi'_2/2)]/t_2$$

$$D=[(R_1\sin\beta\sin\alpha_1-K\cos\theta'_2\sin\psi'_2/2)(v_1t_2+\cos\beta(R_2-R_1))]/t_2$$

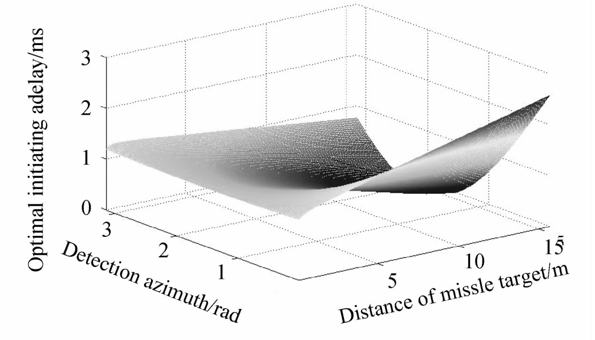
3 Numerical simulation analysis of optimum detonating delay and Azimuth

According to analysis of intersection of missile and target, optimum detonating delay and optimum detonating azimuth are related to pitch angle of missile, pitch angle of the target, the distance between missile and target and azimuth of the initial detection. The models of laser scanning to the target once and twice can be simulated respectively.

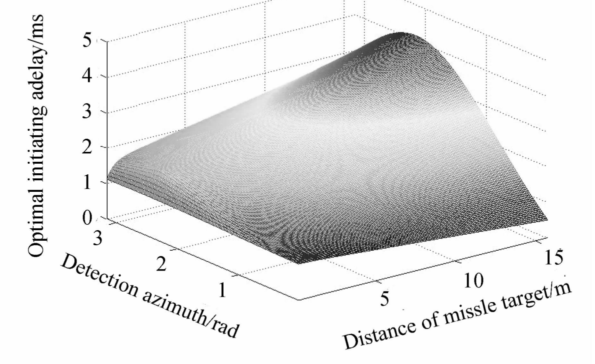
When system scans target only once, assuming that $\theta_1=\pi/2$, $\psi_1=0$, $\psi_2=-\pi/3$, $v_1=300$ m/s, $v_2=600$ m/s, $L_1=1$ m, $K=0.5$ m, $\beta=\pi/3$, $v_0=1\ 500$ m/s. According to the Eq. (10), the relationship between azimuth and the distance between target and missile is shown in Fig. 5. When θ_2 are 0 degree and minus 120°,



(a) Optimum detonating dfelay time with θ_2=0



(b) Optimum detonating delay time with θ_2=−π/3

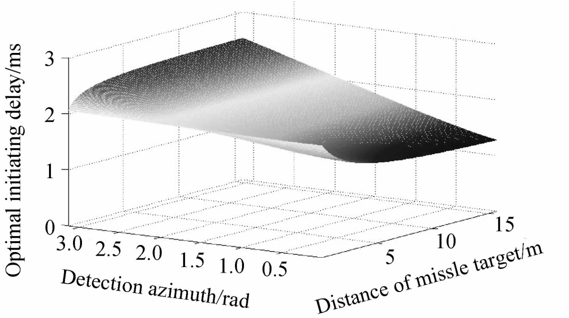


(c) Optimum detonating delay with θ_2=−2π/3

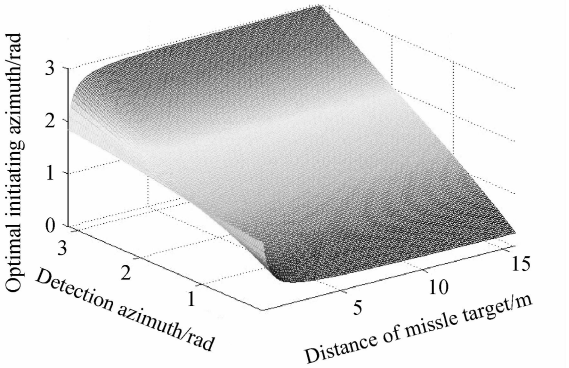
Fig. 5 Optimum detonating delay of single scan

the optimum detonating delay increases with the increasing of the distance between the missile and the target. As azimuth increases, the optimum detonating delay decreases first then increases. When θ_2 is 0°, the range of the optimum detonating delay is 0 ～ 20 millisecond. When θ_2 is $-120°$, the optimum detonating delay increases first, then decreases with the increasing of azimuth. Meanwhile, the maximum value of α_1 is about 1.7. When α_1 is small, the optimum initiation delay decreases with the increasing of the distance between the projectile.

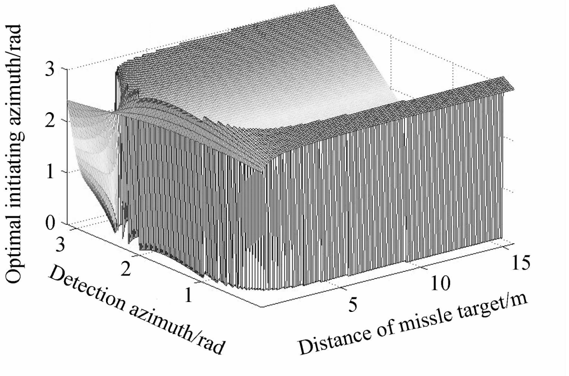
According to the Eq. (11), when θ_2 is 0°, minus 60° and minus 120°, the relationship between detection azimuth and the distance between the target and the projectile is shown in Fig. 6. When θ_2 are 0° and minus 60°, the optimum detonating angle increases with azimuth. As distance between the projectile and the target increaseing , the optimum detonating angle decreases. When θ_2 is minus 120°, optimum initiation angle is 180°, $0<\alpha_1<0.3$. As α_1 is in the scope of 2.8 to 3.14 . the optimum initiation angle is 0. At this time the optimum initiation angle is independent of the detection azimuth and the distance of the projectile-target. In other regions, the optimum initiation angle increases with the increasing of the azimuth and decreases with the increasing of the distance between projectile and target.



(a) Optimum detonating angle with θ_2=0



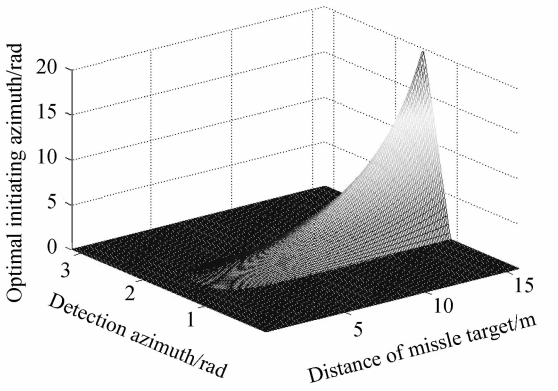
(b) Optimum detonating angle with θ_2=$-\pi/3$



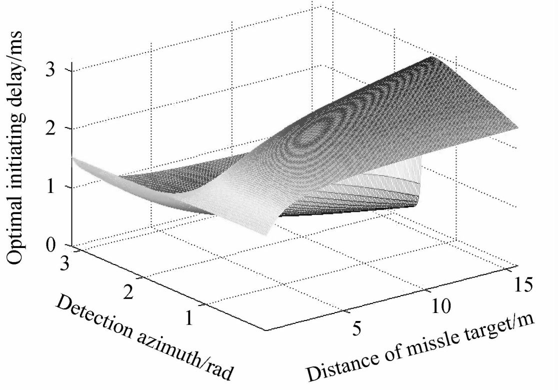
(c) Optimum detonating angle with θ_2=$-2\pi/3$

Fig. 6 Optimum detonating azimuth of single scan

Assume that $v_1=300$ m/s、$L_1=1$ m、$K=0.5$ m、$\beta=\pi/3$、$v_0=1\,500$ m/s、$R_1=20$ m、$\alpha_1=\pi/2$、$t_1=5$ ms. When system scans target twice, according to the Eqs. 14～15, the relationship between the second detection range and the distance between the projectile and the target is shown in Fig. 7. In most of time, the optimum initiation delay time is 0. In the non-zero area, the optimum initiation delay increases with the increasing of distance between projectile-target. In the meantime, as azimuth increases, it increases first, then decreases. The optimum initiation angle increases with the increasing of the detection angle. While $0<\alpha_2<1.57$, the optimum initiation angle increaseing with the increase of the distance between projectile-target, while $1.57\leqslant\alpha_2<3.14$, the optimum initiation angle decreases with the increasing of the distance between projectile-target. When α_2 is 1.57, time will produce a mutation.



(a) Optimum detonating delay time with θ_2=0



(b) Optimum detonating azimuth

Fig. 7 Optimum detonating delay time and azimuth of twice single scan

The optimum initiation strategy: a list of the optimum detonating delay and azimuth is calculated before launching of a missile. The list is arranged in the memory chip of the pulsed laser detection circumferential system. When system detects target first time, the system determines the initiation delay by list and waits for the second detection. If the target is not detected again by system until the time delay is over, then the target will be initiated immediately. If the target is detected again before the end of initiation delay, the delay and Azimuth are directly calculated by using twice best initiation model. Meanwhile the arranged delay time will be cancelled. The optimum detonating delay flow chart is shown in Fig. 8.

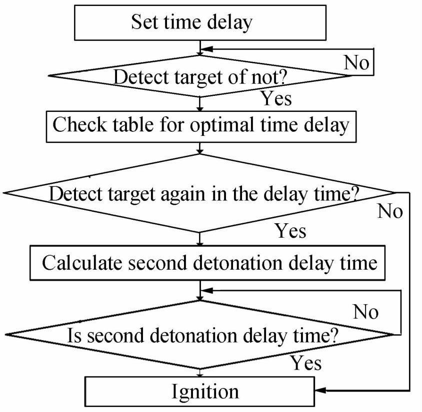


Fig. 8 Flow chart of optimum detonating delay

4 Error analysis

In the measurement of the optimum detonating delay model and optimum detonating azimuth of the single missile-target model, the measuring error of the projectile is greatly influenced by the measurement error of the distance between the projectile and the target. In order to reduce the error, the measurement accuracy of the projectile is very effective. The R_1, R_2, α_1 and α_2 are the main factors to cause errors in the optimal initiation delay and initiation azimuth of the twice missile-target intersection model. On the basis of pulse laser ranging system, the precision can reach centimeter level. Therefore relative error between the missile and the target is small, and its influence can be ignored. The formula of azimuth resolution is $\Delta\alpha = 2\pi w/(60f)$. f is the frequency of laser emission. w is the speed of the motor. In order to improve the resolution, we need to reduce the speed. At the same time, we need to improve the laser emission frequency. However, decrease of the motor speed will affect the target detection probability. Therefore, the reasonable selection of the motor speed in the two detection model is very important in the influence of the error.

5 Conclusion

In this paper single and second missile-target intersection models of optimum detonating delay and detonating azimuth are established for pulsed laser detection system in the body coordinate system. Simulation and analysis of once ignition model are done among the parameters of missile-target distance, detection azimuth, optimum detonating delay time and detonating azimuth. Simulation and analysis of secondary initiation model are done among the parameters of missile-target distance, detection azimuth, target pitch angle, optimum detonating delay time and detonating azimuth. According to the model proposed, the single detonating delay time is set. The optimum time delay and azimuth for twice detection model are accurately calculated, which is the theoretical basis for the directional initiation of the conventional ammunition pulse laser circumferential detection system.

References

[1] XIE Jing, CHEN Hai-qing, TAN Zuo-jun, *et al*. Parameter measurement research of optical transmitter in new laser fuze [J]. *Acta Photonica Sinica*, 2013, **42**(8): 983-987.

[2] GAN Lin, ZHANG He, ZHANG Xiang-jin. Design of narrow pulse-width high speed and complementary drive module for laser fuze [J]. *Acta Photonica Sinica*, 2014, **43**(10): 1014002.

[3] GAN Lin, ZHANG He, ZHANG Xiang-jin. New optical large field receiving technology in laser fuze[J]. *Acta Photonica Sinica*, 2013, **42**(12): 1514-1518.

[4] STEINVALL O. Effects of target shape and reflection on laser radar cross sections[J]. *Applied Optics*. 2000, **39**(24): 4381-4391.

[5] JOHNSON S, CAIN S. Bound on range precision for shot-noise limited ladar systems[J]. *Applied Optics*, 2008, **47**(28): 5147-5154.

[6] ZONG Li-na. Simulation research on fuze-warhead coordination of anti armed helicopter portable rocket bomb[D]. Nanjing: Nanjing University of Science and Technology, 2006.

[7] NYONGESE H O, KENT S. Genetic programming for anti-air missile proximity fuze delay-time algorithms [J]. *IEEE Aerospace and Electronic Systems Magazine*, 2001, **16**(1): 41-45.

[8] ZHU Jing-wei, HU Chang-zhen, TAN Hui-min. The study on determining the optimum detonating delay time of a fuze by using the information on missile[J]. *Journal of Detection & Control*, 2000, **22**(3):24-27.

[9] MENG Xiang-hong, LIU Pei-zhi. The study on the time matching property of the fuzing system for an aimed warhead on air encounter[J]. *Journal of Detection and Control*, 1997, **19**(1): 17-21

[10] ZHU Jing-wei, TAN Hui-min, FAN Yin-hai. A solving method of optimum detonating delay time and detonating direction for aimed warhead[J]. *Journal of Astronautics*, 2003, **24**(2): 198-209

[11] GUO Ze-rong, LI Luo, LI Yuan. Study on the optimum time delay of six laser range-finders for aimed warhead [J]. *Transactions of Beijing Institute of Technology*, 2014, **24**(6): 588-591.

[12] ZHANG Xiang-jin, FENG Ying. Time and space matching characteristic of pulsed laser position detection fuse for aimed warhead[J]. *High Power Laser and Particle Beams*, 2011, **23**(12): 3197-3202.