第 43 卷第 8 期 红外与激光工程 2014 年 8 月
Vol.43 No.8 Infrared and Laser Engineering Aug.2014

Jamming effectiveness of infrared jammer on cross-detector

Tong Qi, Wang Chaozhe, Tong Zhongxiang, Li Jianxun, Jia Lintong, Chai Shijie

(Aeronautics and Astronautics Engineering College, Air Force Engineering University, Xi'an 710038, China)

Abstract: The jamming effectiveness of infrared jammer on cross-detector was researched by modeling and simulating. The mechanism of cross-detector seeker's target recognization and the influences of jamming signal on cross-detector seeker were analyzed. The total simulation model of missile and the target recognization models of reticle seeker and cross-detector seeker under jamming were established. By simulation, jamming effectiveness of IR jammer when jamming two representative kinds of IR missiles in different suppression ratios and duty ratios were researched quantificationally. The results show that IR jammer's jamming effectiveness on cross-detector seeker is much worse than it on reticle seeker; suppression ratio's increase can rise IR jammer's jamming effectiveness; the jamming effectiveness on cross-detector seeker reaches to maximum when duty ratio is 0.5.

Key words: infrared jammer; IR homing missile; cross-detector; jamming effectiveness; simulation
CLC number: TN21 Document code: A Article ID: 1007-2276(2014)08-2496-09

红外干扰机对四元正交探测器的干扰效能

童 奇,王超哲,童中翔,李建勋,贾林通,柴世杰

(空军工程大学 航空航天工程学院,陕西 西安 710038)

摘 要: 采用建模仿真的方法研究了红外干扰机对四元正交探测器的干扰效能。分析了四元正交探测器导引头的目标识别机理和干扰信号对目标识别的影响,建立了导弹总体仿真模型和干扰机干扰下的调制盘导引头和四元正交探测器导引头的目标识别模型。通过仿真定量地比较了不同压制比和占空比下红外干扰机对两种典型红外制导导弹的干扰效果。仿真结果显示,红外干扰机对四元正交探测器导引头的干扰效果明显不如对调制盘导引头的干扰效果;增大压制比可提高干扰机的干扰效能;当占空比为 0.5 时,干扰机对四元正交探测器导引头的干扰效能最大。

关键词: 红外干扰机; 红外制导导弹; 四元正交探测器; 干扰效能; 仿真

收稿日期: 2013-12-11; **修订日期:** 2014-01-18

基金项目: 国家自然科学基金(61203134,61172083)

作者简介: 童奇(1986-),男,博士生,主要从事飞行器作战使用与效能评估仿真等方面的研究。Email:15109288577@163.com

导师简介: 童中翔(1958-),男,教授,博士生导师,博士,主要从事飞行器设计、论证及红外对抗仿真等方面的研究。Email:tzxkgy@163.com

0 Introduction

Infrared jammer is one of those extensively used countermeasure equipments now. Compared with infrared decoy, infrared jammer has many advantages such as working incessantly in a long time, can be reused, and providing self-protection in the whole process of the airplane's taking-off, flight, battle and landing. Infrared jammer has dealt with the threat of the first generation and second generation IR homing missile effectively[1-4]. But IR homing missile's anti-jamming ability is improving constantly. It is very worthy of consideration that whether the infrared jammer could jam the new generation IR homing missile and the jamming effectiveness could be how much.

Currently, the research of the jamming mechanism and jamming effectiveness of the infrared jammer mostly aims at the amplitude modulation infrared seeker representing the first generation and the frequency modulation infrared seeker representing the second generation. But for the third and fourth generation infrared seeker, there are just simple qualitative analyses. For example, Ahn Sang-Ho, Kim Ga-Young, and Sahingil Mehmet Cihan researched the jamming effectiveness of the jammer on amplitude modulation reticle by simulation[5-7]. Fu Wei and Zheng Jianjun researched the jamming mechanism of the jammer on the reticle seeker[8-9]. Li Chenghua studied the jamming effect of the jammer on the reticle seeker by semi-physical simulation[10]. Che Jinxi analyzed the effect of infrared jammer on the infrared imaging detector[11]. The analysis and simulation of the new IR homing missile's anti-jamming ability are mainly aiming at infrared decoy[12-13], which cannot be used in infrared jammer for the basic differences between their jamming mechanisms.

The cross-detector seeker is the typical representative of the third generation infrared seeker. It is generally thought that jamming effect of infrared jammer on cross-detector is not good. But there are few literatures in this field, so a deep discussion and quantitative analysis are meaningful.

The jamming effectiveness of infrared jammer on cross-detector was researched by modeling and simulating in this paper. And the jamming effectiveness in different suppression ratios and duty ratios were also researched. These studies can point ways for the infrared jammer's development and offer method reference for IR countermeasure simulation.

1 Jamming signal of infrared jammer

There are two kinds of infrared jammer: spoofing jammer and pressing jammer[14-15]. Nowadays, most infrared jammers equipped all over the world are spoofing jammers. So this paper mainly discusses the spoofing infrared jammer.

The basic working mechanism of infrared jammer is to produce a jamming signal with stated types and energy, which can be detected by infrared seeker. The jamming signal superposes with the protected airplane's signal in the seeker, thereby forming a movable and illusive target signal. So that the seeker will move to this illusive signal and the missile will lose its true target[16].

So, in order to countermine IR homing missile, the infrared jammer must fulfill the following requests:

(1) The radiation of the jammer should be in the spectral region of infrared seeker(spectrum request);

(2) Jamming pulse can enter into IR homing missile's seeker(shoot directions request);

(3) the jamming energy must be strong enough and the energy could get into the missile's infrared signal processing equip (energy request);

(4) Modulation frequency should be in the pass band of the guidance system circuit of the missile (modulation frequency request).

The infrared jammer is fixed on the target plane. So in the spectral and spatial region of infrared seeker, the superposition signal can get into missile's seeker.

Let $\mathbf{P}_j$ be the radiant power of the infrared jammer. Let Ω be the spatial angle. If the radiation is uniform, the radiant intensity of the IR jammer is:

$$\mathrm{I}_j=\frac{\mathbf{P}_j}{\Omega} \tag{1}$$

In the spectral and spatial region of infrared seeker, the whole radiant power that gets into the missile's seeker is:

$$\mathbf{P}=(\mathrm{I}_p+\mathrm{I}_j)\frac{\mathbf{S}}{\mathbf{L}^2}\tau_1\tau_2 \tag{2}$$

Where I_p is the infrared radiant intensity of the target; $\mathbf{S}$ is the effective optical area of the missile's seeker; $\mathbf{L}$ is the distance between aircraft and missile; τ_1 is the atmospheric transmittance between aircraft and missile; τ_2 is the optical transmittance of the missile's seeker.

In a short time, I_p can be seen constant. I_j changes with time according to certain rules. With different modulation modes, I_j changes according to different rules. In general, I_j modulates according to square wave as shown in Fig.1. In this figure, $\mathbf{B}$ is the amplitude of the square wave. $\mathbf{T}_\theta$ is the duration of the jamming pulse, $\mathbf{T}_j$ is the cycle of the jamming pulse, so the modulation frequency of the jammer is $\omega_j=2\pi/\mathbf{T}_j$. $\mathbf{T}_s$ is the delay time of the jamming pulse, so the delay phase of the jammer is $\gamma=2\pi\mathbf{T}_s/\mathbf{T}_j$. The duty ratio of the jamming signal is $\eta=\mathbf{T}_\theta/\mathbf{T}_j$.

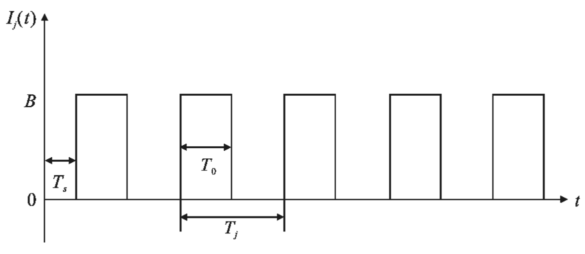

Fig.1 Waveform of jamming signal

The wave form of jammer and target's superimposition signal is shown in Fig.2. $\mathbf{A}$ is the radiant intensity value of airplane. Then suppression ratio $\mathbf{m}=\mathbf{B}/\mathbf{A}$. The superimposition signal $\mathrm{I}_r(t)$ enters into missile's seeker and becomes modulation signal after the seeker's modulating. Then the tracking error is formed by signal processing system to drive the missile. So the effect of superimposition signal $\mathrm{I}_r(t)$ on the IR homing missile mainly depends on the seeker's modulation mode and signal processing method.

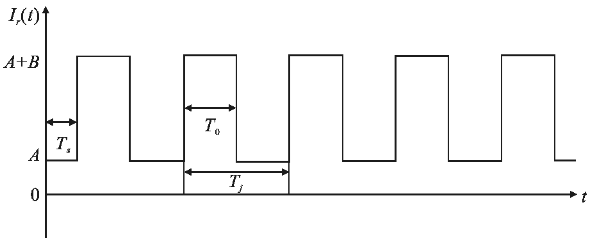

Fig.2 Waveform of jammer and target's superimposition signal

2 Jamming on cross-detector seeker

The cross-detector seeker is the typical representative of the third generation infrared seeker, using pulse phase modulation mode. Its target recognition mechanism differs a lot from the traditional chopper IR seeker's.

2.1 Target recognition mechanism of the cross-detector seeker

The cross-detector's structure and mechanism is shown in Fig.3. Its four cross detector elements locate in the focal plane of the optical system and the target point circles at an angular velocity ω on the focal plane. When the target locates on the optic axis of optics system (ε=0), the center $\mathbf{O}'$ of the point's track laps over the center $\mathbf{O}$ of the cross-detector. Then the point will scan the four detector elements $\mathbf{R}$, $\mathbf{U}$, $\mathbf{L}$, $\mathbf{D}$ in equal interval. The pulse signal in equal interval will output which has no phase error with the reference pulse signal. When the target is not on the

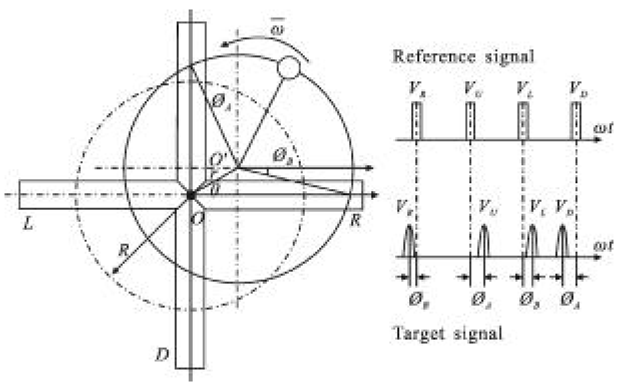

Fig.3 Structure and mechanism of cross-detector

optic axis, the center **O**′ and the center **O** is misaligned. Thus the pulse signal is no longer in equal interval. Its phase error comparison with the reference pulse signal will show the positional information of the target. Meanwhile, with the target point scanning the detector elements, the IR energy received by detector elements changes. So time-changed electrical signal is formed. This electrical signal is the target waveform outputting from the detector[17].

The relationship of the pulse phase ϕ_A, ϕ_B and the target position(polar coordinates(r, θ)) is as follows:

$$\begin{cases} r\cos\theta = \mathbf{R}\sin\phi_A \\ r\sin\theta = \mathbf{R}\sin\phi_B \end{cases} \tag{3}$$

So, the modulation mode of cross-detector seeker is the pulse phase modulation. The pulse phase shows the positional information of the target. And the pulse waveform shows the characteristics of the target. Pulse signal of the target is the basis of the target recognition. The cross-detector seeker adopts a lot of anti-jamming technologies in pulse signal processing. The anti-jamming technologies adopted by a typical cross-detector seeker are summarized as FOV(field-of-view) constringency, gate setting, and waveform memory.

FOV constringency: After getting the target signal, the missile seeker's FOV will constringe to reduce the possibility of the jamming signal's entering. Thus improves the anti-jamming capability.

Gate setting: When target signal appears, the processing circuit outputs trigger signal to generate a gate. The size of the gate should be a little bigger than that of the target signal. The gate should firmly entangle the target signal. Signal in the gate will be processed and the signal out of the gate will be ignored. When the gate is inconsistent with the target, the servo mechanism will control gate generating circuit to make the center of the gate moving to the target, until their centers are superposed.

Waveform memory: If the irradiance of the target point takes a leap (more than the limen), the missile enters into anti-jamming state. The irradiance of the target point last cycle is memorized and the target point is taken as the track. In several cycles, if the target point separates into two points, we can compare the irradiance of these two points with the memorized target point. The point with smaller error is the target and the missile is out of anti-jamming state. If the target point doesn't separate in such a long time, we also think that the missile is out of anti-jamming state. Figure 4 shows the seeker's pulse output in the whole process of jam and target's superposition and separation.

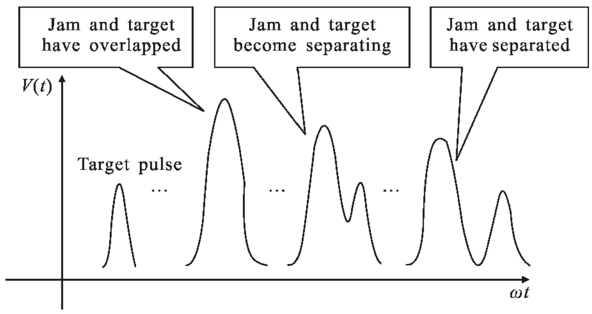

Fig.4 Seeker's pulse output when be disturbed

2.2 Influence of jamming signal on cross-detector seeker

The cross-detector seeker no longer uses reticle to modulate signal. So within a scanning cycle, the time that the target signal gets into the signal processing system is extremely short, and the time for jamming signal is even short. Thus the infrared jammer makes only accidental influence on the pulse signal's waveform. And usually it is not known which random jamming pulse would influence cross-detector seeker's target recognition. The frequency of random jamming pulse signal entering into signal processing system relates to the duty ratio η. The error caused by the random jamming pulse signal entering into signal processing system relates to the suppression ratio **m**. The phase of the jamming signal has no effect on seeker's target recognition. So the effect of duty ratio η and suppression ratio **m** on jamming effectiveness is the key point in this study.

As the jammer is fixed on the target plane, the jamming signal and the airplane signal will enter into the seeker after superposition. So for the three kinds of anti-jamming technologies, the IR jammer can not affect FOV constringency and gate setting. But the jamming signal will increase the target's IR radiation abruptly and thus has an influence on the waveform memory method. The jammer could only change the entered IR radiation power, but could not separate the jamming signal from true target signal. So the IR jammer can only make the missile enter into anti-jamming state accidentally, causing some errors in target tracking. It generates limited influence on IR homing missile's target recognition.

3 Simulation of jamming effectiveness

3.1 Simulation model

The jamming effectiveness of the infrared jammer is related closely to the jamming object, IR homing missile. In this paper, the jamming effectiveness is evaluated by simulating the IR homing missile under infrared jammer's interference. The focus of the simulation is missile's target recognition. The IR homing missile's total simulation model is shown in Fig.5. The guidance law adopts proportional guidance.

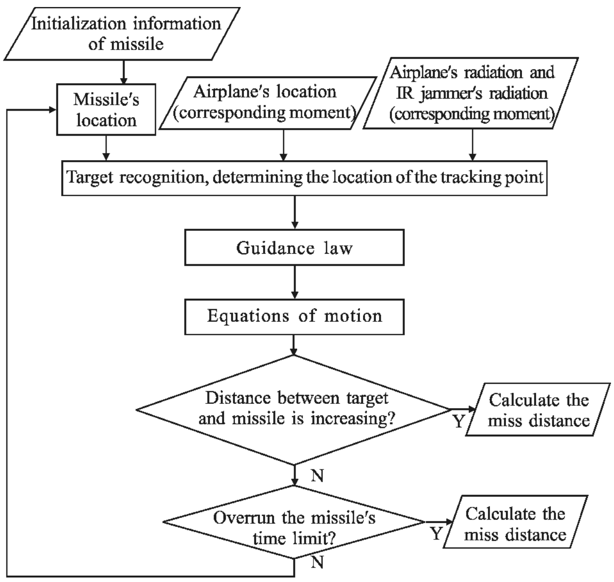

Fig.5 Simulation model of IR homing missile

The simulation method of missile's movement is: confirm the magnitude of missile's velocity by missile's velocity-time figure; confirm the direction of missile's velocity by the proportional guidance equation and missile's maximum permissible acceleration. The miss distance is the distance between airplane's center of mass and missile's center of mass at the moment of missile's exploding.

As the adding of random factors in the simulation, the miss distance also has random element. Take the average miss distance of many times' simulation as an evaluating indicator of jamming effectiveness. Meanwhile the missile has its effective kill radius. When the miss distance is smaller than the effective kill radius, the aircraft is considered to be hit. When the miss distance is bigger than the effective kill radius, the aircraft is considered to be safe. So after many times' simulation, missile's hitting percentage will be worked out, which is taken as another evaluating indicator of jamming effectiveness.

3.2 Simulating of IR seeker's target recognition

3.2.1 The location of target point on the seeker's focal plane

The infrared radiation source is imaged on the seeker's focal plane. In missile's simulation, the 3D coordinates of the radiation source must be projected on the 2D focal plane. Definite a seeker coordinates $\mathbf{O_s x_s y_s z_s}$: origin $\mathbf{O_s}$ is the center of the focal plane; $\mathbf{O_s x_s}$ is along the optical axis directing light's traveling direction; $\mathbf{O_s y_s}$ and $\mathbf{O_s z_s}$ are mutually perpendicular on the focal plane; $\mathbf{O_s y_s}$ is in the vertical plane as is shown in Fig.6(a). The angle between $\mathbf{O_s y_s}$ and the horizontal plane is defined as α. The angle between the projection of $\mathbf{O_s x_s}$ on the horizontal plane and the $\mathbf{O_s x_s}$ of axis system is defined as β. α and β can determine the relationship between geodetic coordinates and seeker coordinates: the transformation matrix from the geodetic coordinates to the seeker coordinates is as follows:

$$\begin{bmatrix} \cos\alpha\cos\beta & \sin\alpha & -\cos\alpha\sin\beta \\ -\sin\alpha\cos\beta & \cos\alpha & \sin\alpha\sin\beta \\ \sin\beta & 0 & \cos\beta \end{bmatrix} \quad (4)$$

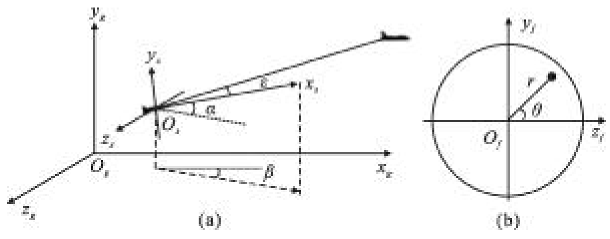

Fig.6 Seeker coordinates and focal plane

The projection of the infrared target on the focal plane is (y_f, z_f), or (r, θ) in polar coordinates as is shown in Fig.6 (b). The size of the missile is smaller compared with the distance to the airplane. So we regard missile's center of mass, O_s and O_f as the same point. Let the distance between missile and airplane be L, and the focus of the optical system be f. Then

$$y_f=\frac{f}{L}y_s,\ z_f=\frac{f}{L}z_s \tag{5}$$

Thus, if the position of the missile and the target is known, the location of the target in the seeker coordinates (x_s,y_s,z_s) can be calculated. And the location of the target point on the seeker's focal plane can be achieved farther.

3.2.2 Simulating of cross-detector seeker's target recognition

Through the analysis of cross-detector seeker's working mechanism in section 2, we know that the infrared jammer only has some influence on the waveform memory method. So only the waveform memory method is considered in simulating. Figure 7 shows the simulation flow.

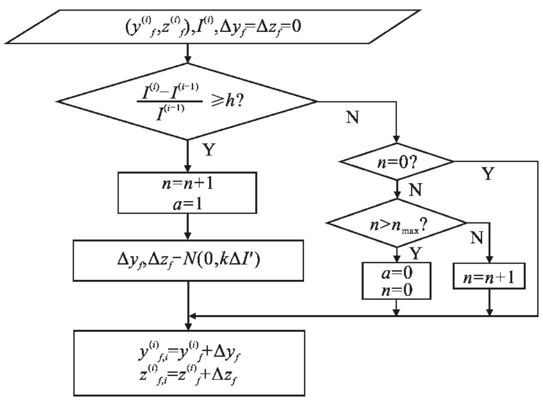

Fig.7 Simulation flow of cross-detector seeker's target recognition

In Fig.7, $\Delta I'=(I^{(i)}-I^{(i-1)}/I^{(i-1)})$ is the relative increment of radiant intensity. And h is relative increment's limen. a is the symbol of the anti-jamming state, which a=1 expresses entering into anti-jamming state and a=0 expresses the contrary. n counts the cycles of entering into anti-jamming state continuously. As the jamming signal is never separated with target signal, the target point's position before entering into anti-jamming state will not be memorized, and will exit anti-jamming state after n_{max} simulation cycles. But every entrance of anti-jamming state will make some effect on the tracking stability. So the errors Δy_f and Δz_f are introduced, which obey normal distribution with average 0 and variance $k\Delta I'$(k is the proportional coefficient). At the beginning, a=0, n=0.

3.2.3 Simulating of reticle seeker's target recognition

For a comparative analysis of infrared jammer's jamming effectiveness on cross-detector seeker and reticle seeker, the target recognition simulation model of reticle seeker is also established.

Through the analysis of reticle seeker's working mechanism, we know that the target tracking of reticle seeker obeys energy centroid principle. The infrared jammer can make a virtual radiation resource according to jamming signal's delay phase γ and suppression ratio m. This virtual radiation resource's coordinate on focal plane is ($y_{f,j}(\gamma)$, $z_{f,j}(\gamma)$), and its radiant intensity is $I_j(m)$. Thus the coordinate of the missile's tracking point on focal plane ($y_{f,t}$,$z_{f,t}$) can be calculated using the following formula:

$$\begin{cases} y_{f,t}=\dfrac{I_p y_{f,p}+I_j y_{f,j}}{I_p+I_j}=\dfrac{y_{f,p}+m y_{f,j}}{1+m} \\ z_{f,t}=\dfrac{I_p z_{f,p}+I_j z_{f,j}}{I_p+I_j}=\dfrac{y_{f,p}+m z_{f,j}}{1+m} \end{cases} \tag{6}$$

3.3 Simulation example

The infrared jammer's jamming effectiveness of mainly concerns with jamming wave band, suppression ratio, modulation frequency, duty ratio and the missile's signal processing method. In this example, the jamming wave band is 1-5 μm. The modulation frequency is the same as that of the missile's signal processing system. The phase varies by the sine law. The target airplane flies at the same altitude with initial velocity 200 m/s and uniform acceleration 5 m/s^2, and its radiant intensity stays invariable. The missile attacks from side-positive direction. The effect of suppression ratio and duty ratio on infrared jammer's jamming effectiveness is researched under above-mentioned simulation settings.

The jamming effectiveness of the infrared jammer on cross-detector seeker missile and reticle seeker missile with different suppression ratios when duty ratio η=0.5 are shown in Fig.8 and Fig.9 respectively. The effective kill radius of these two kinds of missile is 10 m. Comparing these two figures it can be seen that infrared jammer's jamming effectiveness on reticle seeker is good, but that on cross-detector seeker is bad. The more suppression ratio is, the better infrared jammer's jamming effectiveness becomes.

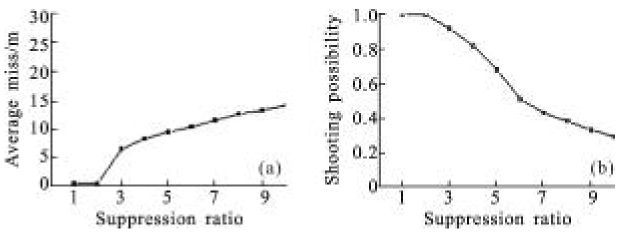

Fig.8 Changes of cross-detector seeker's miss distance and hitting percentage with suppression ratio when η=0.5

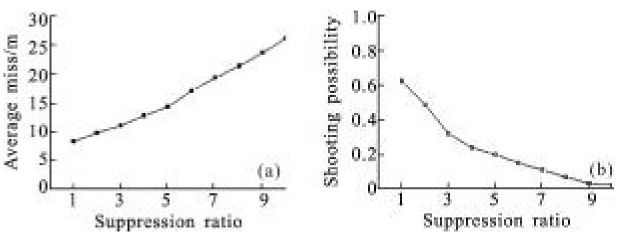

Fig.9 Changes of reticle seeker's miss distance and hitting percentage with suppression ratio when η=0.5

For cross-detector seeker (shown in Fig.8), the limen $\mathbf{h}$=2. When $\mathbf{m}$<3, the jamming signal does not lead the missile into anti-jamming state. The average miss distance and hitting percentage of the missile stays steady. When $\mathbf{m}$>3, the average miss distance of the missile will grow with the increase of the suppression ratio but the jamming effectiveness is still not ideal. When $\mathbf{m}$>6, the missile's hitting percentage becomes dropping to less than 0.5. For reticle seeker (shown in Fig.9), since it tracks the virtual energy centroid, the jamming signal with any intensity can affect the seeker. When $\mathbf{m}$>2, the jamming effectiveness is sizable. These trends are consistent with the results of theoretical analysis and actual combat, so the simulation model's creditability is proved.

Figure 10 shows the changes of infrared jammer's jamming effectiveness on cross-detector seeker with different duty ratios when the suppression ratio is 4. It is clear that, with the increase of the duty ratio, the jamming effectiveness of the jammer firstly gets better and then gets worse. When the duty ratio is 0.5, the jamming effectiveness is the best. This is because that the effect of duty ratio to the infrared jammer's jamming effectiveness on cross-detector seeker lies on the times that the missile enters into anti-jamming

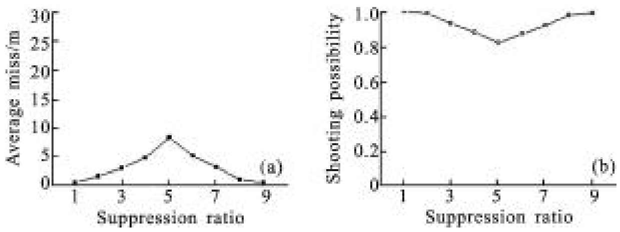

Fig.10 Changes of cross-detector seeker's miss distance and hitting percentage with duty ratio when $\mathbf{m}$=4

state. When the modulation frequency equals to the modulation frequency of the missile's pulse signal approximately, only the probability of missile's signal pulses coming from the jammed signal (the superimposition signal $\mathbf{I}_r(t)=\mathbf{A}+\mathbf{B}$ in Fig.2) and the un-jammed signal(the airplane's signal $\mathbf{I}_r(t)=\mathbf{A}$) is equal, does the missile's signal change most acutely, so the number of times missile entering into anti-jamming state gets the most, thus the total errors in target tracking gets the biggest. When the duty ratio is small, the probability of missile's signal pulses coming from the jammed signal is small. When the duty ratio is large, the probability of missile's signal pulses coming from the un-jammed signal is small. On these conditions, the changes of the signal are small and the number of times missile entering into anti-jamming state is small, so the jamming effectiveness is not so good.

As the reticle seeker doesn't adopt pulse phase modulation mode, the signal processing system can always receive jamming signal. So when the IR jammer jams reticle seeker, duty ratio has little effect on jamming effectiveness. Thus the changes of the infrared jammer's jamming effectiveness on reticle seeker with different duty ratios are no longer analyzed in this paper.

4 Conclusion

Conclusion is drawn in this paper:

(1) Infrared jammer's jamming effectiveness on reticle seeker is better than that on cross-detector seeker. It is due to the different signal processing mode of these two missiles. The better missile's anti-jamming ability is, the worse infrared jammer's jamming effectiveness will be. So it can be predicted that for disturbing the infrared imaging missile, the infrared jammer will work even harder.

(2) Infrared jammer's jamming effectiveness on cross-detector seeker reaches to maximum when duty ratio is 0.5.

(3) Suppression ratio's increase can improve infrared jammer's jamming effectiveness. Only the suppression ratio is bigger than 6 can the jamming effectiveness of the infrared jammer on cross-detector seeker be effective. But the increase of the jamming power is finite. The suppression ratio is hard to reach a value with which infrared jammer's jamming effectiveness on cross-detector seeker is satisfying. So the traditional infrared jammer is not suitable to disturb the new type of IR homing missile. The development trend of IR jamming is laser directional jamming with better directionality and higher jamming power.

The simulation in this paper ignores the effect of environment jamming and the missile's system error on the miss distance calculation. So the miss distance gained from this simulation is smaller than the actual, and the hitting percentage is relatively optimistic. But the conclusions show the essence of the infrared jammer, so they are instructive. The simulation method of infrared jammer in this paper also has reference value.

References:

[1] Cox L J, Batten M A, Carpenter S R, et al. Modelling countermeasures to imaging infrared seekers[C]// Proceedings of SPIE, The International Society for Optical Engineering Technologies for Optical Countermeasures, 2004: 112-119.

[2] Withey M D. Infrared countermeasure flares [J]. Imaging Science Journal, 2010, 58(5): 295-299.

[3] Cao Ruzeng. Operation mechanisms and anti-jamming effectiveness of typical infrared seeker [J]. Aerospace Electronic Warfare, 2005, 21(1): 35-37. (in Chinese)
曹如增. 典型抗干扰红外导引头工作机理及抗干扰性分析[J]. 航天电子对抗, 2005, 21(1): 35-37.

[4] Titterton D H. The interaction in the development of optical missile seekers and jammer technology [J]. Imaging Science Journal, 2010, 58(5): 276-285.

[5] Ahn Sangho, Kim Youngchoon, Bae Taewuk, et al. DIRCM jamming effect analysis of spin-scan reticle seeker [C]// Proceedings -MICC 2009: 2009 IEEE 9th Malaysia International Conference on Communications with a Special Workshop on Digital TV Contents, 2009: 183-186.

[6] Kim Gayoung, Kim Byoungk, Bae Taewuk, et al. Implementation of a reticle seeker missile simulator for jamming effect analysis [C]//2010 2nd International Conference on Image Processing Theory, Tools and Applications, 2010: 539-542.

[7] Sahingil Mehmet Cihan, Uzeler Hande. The effects of directed infrared countermeasure systems on conical scan reticle seekers [C]//2011 IEEE 19th Signal Processing and Communications Applications Conference, 2011: 888-891.

[8] Fu Wei. Jamming mechanism of conical scanning chopper system [J]. Electronic Warfare, 2000(4): 12-16. (in Chinese)
付伟. 对圆锥扫描调制盘系统的干扰机理分析[J]. 电子对抗, 2000(4): 12-16.

[9] Zeng Jianjun, Wu Changluan, Li Ming, et al. Study of the infrared frequency modulated jammer's jamming mechanism

[J]. Laser and Infrared, 2000, 30(1): 36-38. (in Chinese)
曾建军, 伍长銮, 李铭, 等. 调频式红外干扰机机理研究[J]. 激光与红外, 2000, 30(1): 36-38.

[10] Li Chenghua. Research on assessment technology of jamming effectiveness for helicopter-borne IR countermeasure system [D]. Xi'an: Northwestern Polytechnical University, 2007. (in Chinese)
李程华. 直升机载红外对抗系统干扰效果评估技术研究[D]. 西安: 西北工业大学, 2007.

[11] Dong Zejun, Zhang Lei, Zhang Leilei, et al. Study on image jamming effect of infrared imaging system induced by CO_2 laser [C]//Proceedings of SPIE, The International Society for Optical Engineering, 2011: 105-118.

[12] Berggren Jan, Kihlen Ralf. Model for simulation of IR countermeasure effect on IR-seeker/missile [C]//Proceedings of SPIE, The International Society for Optical Engineering Technologies for Optical Countermeasures, 2004: 72-83.

[13] De Jong Wim, Dam Frans A M, Kunz Gerard J, et al. IR seeker simulator and IR scene generation to evaluate IR decoy effectiveness [C]//Proceedings of SPIE, The International Society for Optical Engineering Technologies for Optical Countermeasures, 2004: 100-105.

[14] Karaganov Victor, Law Margaret, Kaesler Mick, et al. Engineering development of a directed IR countermeasure laser [C]//Proceedings of SPIE, The International Society for Optical Engineering Technologies for Optical Countermeasures, 2004: 48-55.

[15] Wu Dan, Ma Chao. Jamming principle and correlation technique of infrared jammer [J]. Shipboard Electronic Countermeasure, 2006, 29(3): 6-9. (in Chinese)
吴丹, 马超. 红外干扰机干扰原理及相关技术 [J]. 舰船电子对抗, 2006, 29(3): 6-9.

[16] Liu Ming, Zhao Tao, Wang Lu. Development of the electrooptical active jamming equipments abroad [J]. Ship Electronic Engineering, 2009(3): 25-28. (in Chinese)
刘铭, 赵涛, 王璐. 国外光电有源干扰装备的发展[J]. 舰船电子工程, 2009(3): 25-28.

[17] Zhang Wenhua, Wang Xing, Ye Guangqiang, et al. Modeling and simulation of infrared cross-detector by time domain[J]. Journal of System Simulation, 2007, 19(19): 4375-4377. (in Chinese)
张文华, 王星, 叶广强, 等. 红外正交四元探测器的时域建模与仿真[J]. 系统仿真学报, 2007, 19(19): 4375-4377.