Research on Influencing Factors of Detection Accuracy Based on Laser Seeker

LIU Shuo, LIU Zhiguo, WANG Shicheng, Qiu Xiong
Xi’an Research Institute of High Technology, Xi’an, China
Liu Shuo e-mail address: 349024993@qq.com

Abstract. In view of the factors affecting the accuracy of laser seeker detection, the working principle of laser seeker receiving laser signal was analysed. The laser convergence route of the optical system was studied. And the working principle of the quadrant detector (QD) is also analysed centrally. The influence of the light spot size and position, and also the different light spot pattern and the response consistency on the detection accuracy of the quadrant detector were analysed theoretically, and the simulation was verified by MATLAB. The results showed that when the light spot was half the size of the QD, the sensitivity and linearity of the detector were best. The quadrant detector had the characteristics of inconsistent response. The characteristics of response conformance was obtained by using mathematical method, so that the effect of its error was negligible by analysis.

1. Introduction
The Laser guided weapons are effective means of precision guidance in battlefield because of their high accuracy and low cost. The classic "PAVE Road" laser guided bombs and the "Copper Snake" laser guided bombs have been developed for several generations in American. The "Thunder" laser guided bombs are also developing rapidly in China. Laser guidance technology has been relatively perfect today. Laser seeker is the core guidance component of laser guided weapons. As the core guidance component of the laser guided weapon, Research institutes and private enterprises are also developing new ideas for laser seekers interiorly. Laser seeker is not only installed on laser guided weapons, but also to be used in hardware-in-the-loop simulation laboratory and electro-optical countermeasure equipment. The accuracy of laser seeker affects the guidance accuracy of laser guided weapons directly. The quadrant detector is an important part of the laser seeker. The accuracy of seeker detection is affected by the response consistency of the detector, the size and position of the light spot. In this paper, the working principle of the laser seeker and quadrant detector are analysed, and the influence of light spot size and location, response consistency of the laser seeker are analysed too.

2. The working principle of laser seeker
The laser seeker is divided into the platform type and the strapdown type. The strapdown laser seeker has also developed considerably, but at present, a large number of laser seeker still adopts platform type. The laser seeker is generally composed of radome, position indicator and electronic module. According to the difference of the position indicator, the seeker can be divided into gyro stabilized optical system, strapdown, universal support, gyro optical coupling and gyro stabilized detector. Generally, the laser semi-active homing seeker adopts the gyroscopic stable optical system.

The main role of the radome is to protect the seeker, and it also plays some role in correcting spherical aberration of optical system [1,2]. The position indicator consists of optical system, quadrant detector and
gyro stabilized platform. The optical system and the quadrant detector are mounted on the gyro platform. The optical system is mounted on the cup type gyro rotor on the outside, it follows the gyro rotor at high speed and searches for laser guided signals ceaselessly by using of the gyroscope precession. Therefore, the optical system must be axially rotationally symmetrical. The accuracy of optical system is increased by increasing its symmetry. The quadrant detector consists of a photodiode, it is installed in the top of gyro inner ring and located on the focal plane of the optical system. The quadrant detector can point to the target steadily with the fixed-axis characteristic of the gyroscope, and also follow the gyro precession (not rotating but moving with the optical axis). The electronic module is composed of A/D conversion and information processing system. The laser guidance signal enters the seeker through the radome. It is reflected by the spherical reflector of the optical system and the plane mirror, converged on the quadrant detector to form a dispersion light spot. The quadrant detector calculates the location of the light spot center according to the difference signals. The quadrant detector output photosensitive signal according to the area of light spot on each quadrant, and the signal go through the preamplifier circuit, weak light signals are amplified to electrical signals. Then the signal is passed through the isolating circuit and relevant information detection circuit to output four DC level signal corresponding to the amplitude of laser guided signal. Analog signals are converted to electrical signals by A/D converter and given to processor processing to get the direction of the target.

3. Optical System

The function of optical system is to accept and converge laser signals to form a dispersion light spot on the quadrant detector. The optical system can be roughly divided into refractive optical system, reflective optical system and catadioptic optical system. The most typical optical system is the Casey Glenn system (R-C structure) [1].

In order to maintain the performance of the laser signal unchanged entering the seeker from all directions, making the front and back arc surfaces of the radome to be all concentric ball. The detector is located on the focal plane of the spherical reflector in a slightly anterior position. Adding a filter in front of the quadrant detector to filter out spectral signals outside the 1064nm, and it reduces the effect of most background light on the quadrant detector.

The sensitivity threshold of laser seeker is an important index related to the guidance accuracy and guidance distance of seeker. Reducing the sensitivity threshold of the seeker can improve the guidance distance of the laser seeker. In the ideal condition, the sensitive threshold of the receiving energy of the seeker is $E_{th}$ [2].

$$ E_{th} = \frac{E_{min}}{A_T} \quad (1) $$

Thereinto, $E_{min}$ is the least measured energy for the four quadrant detector, $A_T$ is the effective area of the entrance pupil of the seeker, $T_e$ is the energy transmittance of the optical system. From the formula, the way to reduce the sensitivity threshold of the seeker is to improve the sensitivity of the quadrant detector and increase the effective area of the guiding head to the pupil.

4. Working principle of four quadrant detector

The quadrant detector is a photodiode photosensitive element. It is divided into PIN photodiode APD photodiode. The quadrant detector is demarcated by cartesian coordinate system, and it is divided into four quadrant regions (A, B, C, D). The laser signal enters the seeker and go through the optical system, forming a dispersion spot on the quadrant detector. According to the difference size of the light spot area on the four quadrants ($S_A$, $S_B$, $S_C$, $S_D$), the four quadrants output different photosensitive currents ($I_A$, $I_B$, $I_C$, $I_D$). The signal processing circuit calculates the position deviation signal according to the current, and gets the light spot position [3].

It is assumed that the light spot is a homogeneous spot. The radii of photosensitive area of the quadrant detector is R, the radius of the spot is r, the actual coordinates of the spot center is ($x$, $y$), the
definition of A is the calculation offset of the spot position after normalization. The purpose of normalization is to eliminate the effect of energy changes in the quadrants on the results. That is:

\[
\begin{align*}
E_x &= \frac{(I_A + I_D) - (I_B + I_C)}{I_A + I_B + I_C + I_D} \\
E_y &= \frac{(I_A + I_B) - (I_C + I_D)}{I_A + I_B + I_C + I_D}
\end{align*}
\]  

(2)

Photocurrent on photodiode has a linear relationship with illumination. Therefore, the photocurrent of each quadrant is directly proportional to the energy received. It is assumed that the light spot on the detector is a uniform spot. The area of the light spot is proportional to the energy in the quadrant, then

\[
I_i = k * S_i, \quad k \text{ is the proportional coefficients. That is:}
\]

\[
\begin{align*}
E_x &= \frac{(S_A + S_D) - (S_B + S_C)}{S_A + S_B + S_C + S_D} \\
E_y &= \frac{(S_A + S_B) - (S_C + S_D)}{S_A + S_B + S_C + S_D}
\end{align*}
\]  

(3)

According to the formula (2), the result is as follows:

\[
\begin{align*}
d_x &= \frac{1}{\pi r^2} [2r^2 \arcsin(\frac{x_0}{r}) + 2x_0 \sqrt{r^2 - x_0^2}] \\
d_y &= \frac{1}{\pi r^2} [2r^2 \arcsin(\frac{y_0}{r}) + 2y_0 \sqrt{r^2 - y_0^2}]
\end{align*}
\]  

(4)

Supposed that, the radius of the quadrant detector is R=2mm, the radius of the spot is r=1mm. Obtained by simulation, get the relationship between the actual position of the light spot on the detector and the corresponding solution \(E_x\), as shown in the Figure 1. As seen from the diagram, there is a good linear relationship between the calculated value and the actual value at [0, 0.6]. As the light spot is getting farther away from the center of the detector, the larger the nonlinear error is. When \(x \geq 1\), the second and third quadrant have no light spot, then \(E_x = 1\). The same relationship between \(E_y\) and \(y\) can be obtained.

Fig.1 the diagram of relationship between the \(E_x\) and \(x\)

The above sum-difference algorithm is a common method for general seeker. After then, many other scholars have studied other algorithms, such as database query method, polynomial fitting method, Infinite integral fitting algorithm and Composition fitting algorithm, etc [4,5].
4.1. Analysis of the size and position of the diffuse speckle

According to formula (3), we can see that the spot position offset is not only related to the actual position of the light spot, but also related to the light spot size on the quadrant detector. Due to the existence of dividing line dead zone in the quadrant detector, the area of the light spot must be larger than that of dead zone in the center of the detector. Similarly, if the light spot is covered with four quadrant detectors, the detector cannot be able to output the sum-difference signal. It's obviously wrong. So, the range of the value $r$ is $\sqrt{2} \leq r \leq R$, suppose that $R=2$mm, Take the $r = 0.5$, $0.75$, $1$, $1.25$, $1.5$. The relationship between the offset $E_x$ and the actual position $x$ of the spot in the $x$ axis direction was simulated by using MATLAB.

![Fig.2 diagram of light spot offset $E_x$ in different spot radius](image)

Figure 2 is the normalization curve of the calculated offset value, which of the signal is output by the quadrant detector. When the spot radius $R$ is different from $R/4 \sim 3R/4$, the accuracy and sensitivity of the corresponding deviation signals are also different. When the light spot on the detector is small, the measuring range of light spot actual position is smaller, only about $-0.5 \sim 0.5$ can be measured. But the slope is larger in the vicinity of the center, the sensitivity of the detection is high. When the light spot is large, the measurement range of the actual position is large. But the slope of the curve near the center is smaller, so the sensitivity is low. Only when the spot radius is half of the detector radius, there is a good linear relationship between the offset value and the actual position of the spot, and the sensitivity is high. Moreover, the linearity of the light spot near the center is good [6].

The size of the spot of the detector is related to the structure of the optical system. The position of the four quadrant detector in the front of the focal plane of the spherical reflector. Control the size of the light spot on the quadrant detector by adjusting the focal length of the detector and focal plane. It is assumed that the amount of defocus amount is $\Delta f$, the incident light spot diameter of the seeker is $\Phi$, the focal length of a spherical mirror is $f$. Then the formula (5) is obtained.

$$\frac{2r}{\Phi} = \frac{\Delta f}{f}$$  \hspace{1cm} (5)

When the size of the spot on the detector satisfies the relationship $r=R/2$, the precision of the detector is high. Making the size of the spot to be satisfied by adjusting the position of the four quadrant detector on the optical axis and relative exit pupil $L$.

4.2. Analysis of the influence of dispersion spot energy distribution

The energy distribution of the dispersion spot is usually divided into three cases: uniformity distribution, Gaussian distribution and airy distribution. The influence of the light spot size and position to the detection accuracy of quadrant detector is studied under the condition of uniformity spot in the above. In the actual situation, the detector is on the location little away from the focal plane of the optical system. The laser passes through the optical system, the energy of the light spot is close to the Gaussian
distribution, then get formula (6)[7,8]. In the formula (6), \( \omega \) is the radius of Gaussian spot, \( \text{erf}(x) \) is the function of Gaussian error. If Figure (6) the uniform distribution and a Gauss distribution, There is the curves of the relationship between \( E_x \) and the actual position \( x \) of the light spot in the uniformity distribution and Gaussian distribution. The Gaussian distribution curve has a high slope near the center position, and the sensitivity is good. But the actual location of the light spot is small.

\[
E_x = \text{erf} \left( \frac{\sqrt{2} x_0}{\omega} \right)
\]  

(6)

Fig.3 the diagram of light spot offset \( E_x \) in different spot mode

4.3. Analysis of four quadrant response conformance

Response consistency refers to the consistency of the current responsiveness output by four quadrant. Response consistency is an important indicator of the quadrant detector. Suppose that in the case of uniformity illumination, the laser signal AC of the quadrant detector is \( I(t) \). The \( i_{th} \) quadrant output the AC signal is the function \( f_i(t) \), the current response degree is \( R_i \). Then get formula (7).

\[
R_i = \frac{f_i(t)}{I(t)}
\]

(7)

Supposed that the response conformance of the first and second quadrant is \( \gamma_{12} \), the response conformance of the quadrants detector is \( \gamma \). According to the definition of response consistency, get the relations \( \gamma_{12} \leq 1, \gamma \leq 1 \), thus define the variable \( \gamma_{12} \) according to the formula \((R_i - R_j)^2 \geq 1\).

\[
\gamma_{12} = \frac{2R_i R_j}{R_i^2 + R_j^2}
\]

(8)

Only when \( R_1 = R_2 \), then \( \gamma_{12} = 1 \). Also according to the relationship between the \( R_1, R_2, R_3 \) and \( R_4 \), get the variable \( \gamma \).

\[
\gamma = \frac{2R_1 R_2 + 2R_1 R_3 + 2R_1 R_4 + 2R_2 R_3 + 2R_2 R_4 + 2R_3 R_4}{(R_1^2 + R_2^2)^2 + (R_1^2 + R_3^2)^2 + (R_1^2 + R_4^2)^2 + (R_2^2 + R_3^2)^2 + (R_2^2 + R_4^2)^2 + (R_3^2 + R_4^2)^2}
\]

\[
= \frac{2R_1 R_2 + 2R_1 R_3 + 2R_1 R_4 + 2R_2 R_3 + 2R_2 R_4 + 2R_3 R_4}{3(R_1^2 + R_2^2 + R_3^2 + R_4^2)}
\]

(9)

Obtain a series of value \( f_{ik} \) from the function \( f_i(t) \) by the experiment. Get the following function.

\[
\gamma_{ik} = \frac{2f_{ik} f_{2k} + 22f_{ik} f_{3k} + 22f_{ik} f_{4k} + 2f_{2k} f_{3k} + 2f_{2k} f_{4k} + 2f_{3k} f_{4k}}{3(f_{ik}^2 + f_{2k}^2 + f_{3k}^2 + f_{4k}^2)}
\]

(10)

Obtain the quadrant response degree \( \gamma \) by taking the mean of \( \gamma_{ik} \).
\[ \gamma = \frac{1}{N} \sum_{k=1}^{N} \gamma_k \]  

(11)

5. Conclusion

In this paper, through theoretical analysis and MATLAB simulation, the influence of the light spot size and position, also the different light spot pattern and the response consistency on the detection accuracy of the quadrant detector were obtained. When the light spot is larger, the measurement range of the actual position is larger, and the sensitivity is lower. Contrarily, the light spot is smaller, the actual position measurement range is smaller, and the sensitivity is higher, the linear performance of the light spot near the center position is good. We get the conclusion through a mathematical method that the error effect caused by the quadrant response inconsistency is negligible.

References

[1] Li Rizhong. Development of Simulation Seeker for Semi-active Laser-guided Weapon Simulation System [D]. National University of Defense Technology, 2004.
[2] Li Haifei. The Development on The Detecting And Controlling Circuit of Semiactive Laser Guidance Seeker [D]. National University of Defense Technology, 2005.
[3] Wei Wenjian, Qin Shiqiao, Zhang Baoding, Li Hua, Zhan Dejun. Design on the optical system of laser semi-active seeking guided hardware-in-the-loop simulation seeker [J]. Infrared and Laser Engineering, 2008(02):322-325.
[4] Chen Mengwei, Yang Yingping, Jia Xintign, Leng Fang. Research of Center Location Algorithm for Four Quadrant Detector[J].Journal of Wuhan University of Technology (Transportation Science & Engineering), 2013, 37(05):1124-1127.
[5] Liang Weiw, Huang Zhenyu, Zhang Wenpan, Yin Ruiguang, Liu Yanfang. Study on error signal of quadrant detectors in laser seekers [J]. Laser Technology, 2014, 38(04):569-573.
[6] Wu Jiabin. The Research for Technology of High Precise Laser Facula Position Detection Based on the Quadrant Detector [D]. Changchun Institute of Optics, Fine Mechanics and Physics Chinese Academy Sciences, 2016.
[7] Zhang Lei, Zhang Guoyu, Liu Yunqing. Affecting Factor for Detection Accuracy of Four-Quadrant Detector [J]. Laser Technology, 2012, 39(06):121-125.
[8] Fang Xulai. Four Quadrant Detector Applied Research In Space Laser Communication [D]. Changchun University of Science and Technology, 2015.
[9] Liu Huabai. Design of Target Azimuth Detecting Circuit in Hardware-in-the-Loop Simulation System of Semiactive Laser Guidance [D]. National University of Defense Technology, 2008.