Photoelectric detection technology of laser seeker signals

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Abstract: The measurement of the rolling angle of the projectile is one of the key technologies for the terminal correction projectile. To improve the resolution accuracy of the rolling angle in the laser seeker weapon system, the imaging model of the detector, calculation model of the position and the signal-to-noise ratio (SNR) model of the circuit are built to derive both the correlation between the resolution error of the rolling angle and the spot position, and the relation between the position resolution error and the SNR. Then the influence of each parameter on the SNR is analyzed at large, and the parameters of the circuit are determined. Meanwhile, the SNR and noise voltage of the circuit are calculated according to the SNR model and the decay model of the laser energy. Finally, the actual photoelectric detection circuit is built, whose SNR is measured to be up to 53 dB. It can fully meet the requirement of 0.5° for the resolution error of the rolling angle, thereby realizing the analysis of critical technology for photoelectric detection of laser seeker signals.

Keywords: laser seeker, rolling angle, error of position, signal-to-noise ratio (SNR), photoelectric detection.

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1. Introduction

The laser semi-active search guide weapon system (LSSGWS) is featured with high guidance accuracy, strong anti-jamming ability, low cost, simple structure and usability, etc. It is extensively applied to the weapons and most frequently used as photoelectric precision guided weapon [1–5]. The working principle of LSSGWS is as follows. When the target is irradiated with the encoded laser beam on the airborne or ground surface, the laser seeker can receive the echo information of the diffuse reflection, and the information is transmitted to the guidance system to track the target. At the same time, the deviation signal is transmitted to the projectile control system to guide the projec-

tile to the target.

The LSSGWS working function mainly depends on the laser seeker head on the front end of the weapon [6–8]. According to the correction strategy, the projectile obtains the steering instruction of the actuator. When the projectile rolls to a specific angle, the actuator is started up, which produces the controlling force to correct the trajectory [9–11]. Thus, the accuracy of measurement of the rolling angle has a direct bearing upon the correct accuracy [12].

When the laser with repeated frequency of 10–20 Hz is used for guidance, the detector mostly adopts the optical position sensor with quick velocity response and will output the nanosecond impulse signal [13]. During the actual appliance, the performance of the detecting instrument will be influenced and limited by the noise and interference [14–17]. In the process of laser guidance, the optical signal is relatively weak when the target has low reflectivity or a large transmission range. While the primary function of the photoelectric detection circuit is to eliminate the influence of noise and interference on the detector and raise the signal-to-noise ratio (SNR) of its circuit as far as possible, which can be obtained to a higher guidance accuracy.

Related scholars analyzed the influencing factors of noise in the photoelectric detection circuit and the problems requiring attention in the design of the detection circuit [18–24]. Liang et al. analyzed the influencing factors for position accuracy of the four-quadrant detector [6]. Jiang et al. tested and analyzed the equivalent noise of the position sensitive detector (PSD) measuring circuit, obtaining a series of simulation results [25]. However, the existing analyses on the photoelectric detection circuit are all based on the quantitative analysis, noise model analysis and analog simulation analysis instead of making specific analyses on the characteristics of the laser homing head signal. Thus, the relation between the position resolution accuracy and the resolution error of the rolling angle on the imaging face of the photosensor is firstly analyzed according to the trajectory information and the characteristics of

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the correction projectile based on the laser homing head, deducing the resolution error relation of error determination position for the rolling angle. Then the SNR model is analyzed by the relation between the position error and the SNR. Finally the factors influencing the circuit SNR are analyzed. According to the characteristics of the laser homing head signal, a low noise photoelectric detection circuit is built. In addition, the related measurement is carried out to verify whether the designed circuit can deliver the error precision of rolling angle resolution.

2. Resolution error of rolling angle and spot position

The LSSGWS of the schematic diagram of the working principle is illustrated in Fig. 1.

Fig. 1 LSSGWS of the schematic diagram of the working principle

In order to illustrate the relationship between the imaging plane of the projectile and the real target point on the ground, the imaging model is established as Fig. 2.

Fig. 2 Schematic diagram of the imaging model of photoelectric position sensor

In the figure above, the $O-xyz$ is the ground coordinate system, and the coordinate system $O_1 - x_1y_1z_1$ is obtained by transferring from the ground coordinate system to the projection point O_1 of the projectile on the ground. Definition of the projectile coordinate system $O_1 - x_2y_2z_2$: The coordinate system $O_1 - x_1y_1z_1$ is rotated ψ clockwise around O_1y_1 axis, and Ψ is the yaw angle. Point C is the position of the detector lens on the projectile; Point B is the intersection point of the projectile shaft axis or the optical axis and the axis x_2 of the projectile; Point A is the location of the target point; ϑ is the pitch angle of the projectile. An aspect angle of the projectile ε is defined as the angle between the projectile shaft axis and the connection between the projectile and the target, which represents the degree of deviation from the target.

At time t , $T(y_g, z_g)$ is the projection point of the target point measured on the imaging surface of the detector; $C(x_0, y_0, z_0)$ is the point of the ground system coordinates; θ is the pitch angle, ψ is the yaw angle, γ is the roll angle. The lens imaging relationship between the light spot coordinate T on the imaging surface of the sensor and the imaging point A in the missile body coordinate system $O'_1 - x_1y_1z_1$ of the projectile, is shown in Fig. 2. Ignoring the installation error between the sensor and the lens, the light spot coordinate T on the imaging surface of the sensor is transformed into other coordinates. The specific conversion process is as follows.

Firstly, the coordinates of the imaging point T in the coordinate system $O_1 - x_1y_1z_1$ are calculated, and this process is used to realize by the coordinate transformation matrix.

Secondly, it is known that the position of the projectile C is $(0, y_0, 0)$ under the coordinate system $O_1 - x_1y_1z_1$. Because two points determine a straight line, the intersection point of the straight line TC and the plane $x_1O_1z_1$ is the position coordinates of the target point A , shown as Fig. 2.

Thirdly, the point A is converted to the ground coordinate system O_1-xyz . After the above derivation, the conversion of the target point and the light spot can be linked.

From the above analysis, the calculation accuracy of the roll angle of the projectile is related to the seven parameters of $x_0, y_0, z_0, \vartheta, \psi, y_G, z_G$. The error of the roll angle is $\Delta\gamma$, and the seven errors are $\Delta x_0, \Delta y_0, \Delta z_0, \Delta\vartheta, \Delta\psi, \Delta y_G, \Delta z_G$. The error can be theoretically obtained as below:

$$\Delta\gamma = \left| \frac{\partial\gamma}{\partial x_0} \right| \Delta x_0 + \left| \frac{\partial\gamma}{\partial y_0} \right| \Delta y_0 + \left| \frac{\partial\gamma}{\partial z_0} \right| \Delta z_0 + \left| \frac{\partial\gamma}{\partial \vartheta} \right| \Delta\vartheta + \left| \frac{\partial\gamma}{\partial \psi} \right| \Delta\psi + \left| \frac{\partial\gamma}{\partial y_G} \right| \Delta y_G + \left| \frac{\partial\gamma}{\partial z_G} \right| \Delta z_G \quad (1)$$

with

$$\left\{ \begin{array}{l} \frac{\partial \gamma}{\partial x_0} = -\frac{\sin \vartheta \cdot x_1 + b_1 \cdot \cos \vartheta \cdot \cos \psi}{d_0} \\ \frac{\partial \gamma}{\partial y_0} = -\frac{\cos \vartheta \cdot x_1 + b_1 \cdot \sin \vartheta \cdot \cos \psi}{d_0} \\ \frac{\partial \gamma}{\partial z_0} = \frac{b_1 \cdot \sin \psi}{d_0} \\ \frac{\partial \gamma}{\partial \vartheta} = -\frac{d_1 \cdot x_1 + b_1 \cdot \sigma}{d_0} \cdot \lambda \\ \frac{\partial \gamma}{\partial \psi} = -\frac{b_1 \cdot \tan \varepsilon \cdot d_2}{d_0} \cdot \kappa \\ \frac{\partial \gamma}{\partial y_G} = -\frac{b_1 \cdot f \cdot y_G}{(y_G^2 + z_G^2)^{3/2} \cdot d_0} + \frac{z_G}{y_G^2 + z_G^2} \\ \frac{\partial \gamma}{\partial z_G} = -\frac{b_1 \cdot f \cdot z_G}{(y_G^2 + z_G^2)^{3/2} \cdot d_0} - \frac{y_G}{y_G^2 + z_G^2} \end{array} \right. \quad (2)$$

and

$$\left\{ \begin{array}{l} \phi_1 = \arctan(\tan \vartheta \cdot \sqrt{1 + (\tan \psi)^2}) \\ \phi_2 = \arctan\left(\frac{\tan \psi}{\sqrt{1 + (\tan \vartheta)^2 + (\tan \vartheta)^2 (\tan \psi)^2}}\right) \\ b_1 = -\Delta x \cdot \sin \phi_1 + \Delta y \cdot \cos \phi_1 \\ d_0 = x_1^2 \cdot \tan \varepsilon \sqrt{1 - b_1^2 / (x_1 \cdot \tan \varepsilon)^2} \\ d_1 = -\Delta x \cdot \cos \phi_1 - y_0 \cdot \sin \phi_1 \\ d_2 = -\Delta x \cdot \cos \phi_1 \cdot \sin \phi_2 - \Delta y \cdot \sin \phi_1 \cdot \sin \phi_2 + \\ \quad \Delta z \cdot \cos \phi_2 \\ x_1 = \Delta x \cdot \cos \phi_1 \cdot \cos \phi_2 + \Delta y \cdot \sin \phi_1 \cdot \cos \phi_2 + \\ \quad \Delta z \cdot \sin \phi_2 \\ \lambda = \frac{\sqrt{1 + (\tan \psi)^2}}{\left[\frac{(\cos \vartheta)^2 + (\cos \vartheta)^2 (\tan \vartheta)^2 +}{(\cos \vartheta)^2 (\tan \vartheta)^2 (\tan \psi)^2} \right]} \\ \kappa = \frac{(\tan \vartheta)^2 \sqrt{1 + (\tan \vartheta)^2 + (\tan \vartheta)^2 (\tan \psi)^2}}{(\tan \vartheta)^2} \\ \sigma = -\Delta x \cdot \sin \phi_1 \cdot \cos \phi_2 - \Delta y \cdot \cos \phi_1 \cdot \cos \phi_2 \end{array} \right. \quad (3)$$

It is easy to get the error model of the rolling angle solution from above. To analyze the influence of precision of the rolling angle solution of the spot location error Δy_G and Δz_G on the sensor imaging surface, it is assumed that the nominal value of the other variables is constant and the error is zero, and the influence is discussed about the single error on the accuracy of the rolling angle solution.

The 120 mm laser semi-active correction projectile with a tail stabilizer is the study object. The initial velocity is $v = 340$ m/s and the projectile mass is $m = 13.45$ kg. In the simulation process, the range of $(\Delta y_G, \Delta z_G)$ is from -0.1 mm to 0.1 mm. After substituting them into the error model of the rolling angle solution, the total error of the rolling angle is illustrated as Fig. 3.

Fig. 3 Influence of the spot location error on the accuracy of the roll angle calculation

In the simulation process, because the starting light spot is assumed to fall on the positive and negative 45° lines through the coordinates of the origin, the influence factor is equal. By simulation analysis, if the error of the spot position is only considered and the error of the rolling angle is controlled in the range of 0.5° , the position error should be controlled within the range of $50 \mu\text{m}$.

3. Design of photoelectric detection circuit

In order to make the signal output of the photoelectric sensor easy to detect, the first thing how to convert the current signal from the sensor into a better measured voltage signal is considered. The signal of current source is converted into a voltage source, which can be achieved by using a voltage parallel negative feedback circuit [26–28].

Because the attenuation of the laser energy in the atmosphere is very serious, the guidance distance of the missile system is thousands of meters, and the output current signal of the sensor is so weak, it is easily disturbed by other various signals. Therefore, it is beneficial to increase the stability and anti-interference ability of the circuit by choosing reasonable electrical parameters according to the accuracy of modification.

3.1 SNR and photocurrent

Based on the above analysis, it can be seen that the schematic diagram of the constant current spot measuring circuit for two-dimensional (2-D) photoelectric sensor light spot mainly consists of the negative feedback circuit, the addition circuit, the subtraction circuit and the division circuit.

Because the illuminant is mostly the pulsed source light in the real application, the first-stage amplifier in the direct-current measurement schematic diagram is added with the filter circuit. Besides, the resolving circuit of the spot point is realized through analog circuit. In addition, the number of bits and velocity of existing analog-to-digital converter (ADC) chip are enough to replace the functions of addition and division, which are prone to produce noise caused by temperature and environment.

Thus, the addition and division of the software are used to replace the function of analog circuit, as shown in Fig. 4

in details. The electric current signal output by the photoelectric position sensor is processed in the amplifier in Fig. 4. Then it is directly sent to the data acquisition chip for data acquisition unit (DAU). After related operation, the position information of the spot point can be calculated.

Fig. 4 Schematic diagram of signal processing circuit with software instead of the operator

From Fig. 4, it is known that the noise of the amplifier and other devices, the inequality of the resistance of resistor, the offset without elimination, and the temperature drift will lead to the error in the calculation of the coordinates. To derive the position resolution of the 2-D photoelectric position sensor, it is assumed that the incident light moves Δx and Δy on the imaging face, and then the photocurrent of the corresponding pole will change slightly. The change is recorded as ΔI shown in Fig. 5.

Then (2) can be obtained.

$$\begin{aligned}
 x &= \frac{Lx}{2} \frac{(I_{X2} + I_{Y1}) - (I_{X1} + I_{Y2})}{I_{X1} + I_{X2} + I_{Y1} + I_{Y2}} = \\
 &\frac{Lx}{2} \frac{I_1 - I_2}{I_{X1} + I_{X2} + I_{Y1} + I_{Y2}} \rightarrow \\
 \Delta x &= \frac{\Delta I_X - \Delta I_Y}{I_o} Lx \\
 y &= \frac{Ly}{2} \frac{(I_{X2} + I_{Y2}) - (I_{X1} + I_{Y1})}{I_{X1} + I_{X2} + I_{Y1} + I_{Y2}} = \\
 &\frac{Ly}{2} \frac{I_3 - I_4}{I_{X1} + I_{X2} + I_{Y1} + I_{Y2}} \rightarrow \\
 \Delta y &= \frac{\Delta I_X + \Delta I_Y}{I_o} Ly
 \end{aligned} \quad (4)$$

Fig. 5 Relationship between the displacement of the spot on the imaging surface and the photocurrent

and

$$I_1 = I_{X2} + \Delta I_X + I_{Y1} - \Delta I_Y \quad (5)$$

$$I_2 = I_{X1} - \Delta I_X + I_{Y2} + \Delta I_Y \quad (6)$$

$$I_3 = I_{X2} + \Delta I_X + I_{Y2} + \Delta I_Y \quad (7)$$

$$I_4 = I_{X1} - \Delta I_X + I_{Y1} - \Delta I_Y \quad (8)$$

In the real application, when neglecting the machining error ($L = Lx = Ly$), (9) can be obtained.

$$\Delta x + \Delta y = 2 \cdot \frac{\Delta I_X}{I_o} L \quad (9)$$

According to (9), the resolution of the circuit is determined by the SNR of the detection circuit. The larger the photocurrent and the smaller the noise, the higher the resolution.

According to the correction accuracy, the location error of the spot can be easily controlled in the range of 50 μm . Assuming that the location error is $\Delta x = \Delta y = \pm 25 \mu\text{m}$, the SNR of the circuit is up to 53 dB according to (9).

3.2 Influence factors of noise

According to Section 3.1, if reaching the desired positioning error, the SNR of the circuit is up to 480:1. The noise of the circuit is the main factor that affects the SNR of the detection circuit. Thus the next step is to deduce the SNR of the entire circuit from the noise model of the circuit.

The noise of an operational (OP) amplifier can be characterized by three equivalent noise sources, including current noise source with two spectral densities of I_{nn} and I_{np} and a voltage noise source with a spectral density of e_n . These three noise sources are basically independent [29], and the circuit can be simplified as Fig. 6. In this picture,

I_O is photocurrent, I_D is dark current, R_F is feedback resistor, C_F is parasitic capacitance of feedback resistor and V_O is output voltage.

Fig. 6 Noise model circuit of 2-D photoelectric sensor

The noise root mean square (RMS) voltage of the circuit [25] is

$$V_n = \sqrt{V_O} \quad (10)$$

with

$$V_O = V_s^2 + V_j^2 + V_{en}^2 + V_{R_F}^2 + V_{in}^2. \quad (11)$$

Among them (the unit is Volt/V and the same below): the bulk noise of photocurrent dark current is $V_j = R_F \cdot \sqrt{4kTB/R_{ie}}$. B represents the bandwidth of the circuit, and q represents the amount of electron charge, $q = 1.6 \times 10^{-19} C$; the equivalent internal resistance thermal noise is $V_j = R_F \cdot \sqrt{4kTB/R_{ie}}$. T represents the absolute temperature. k represents Boltzmann constant, $k = 1.38 \times 10^{-23} J/K$; the equivalent value of the input voltage noise of the amplifier at the output terminal is $V_{in} = (1 + \frac{R_F}{R_{ie}}) \cdot en \cdot \sqrt{B}$; the equivalent value of the input current noise of the amplifier at the output terminal is $V_{en} = R_F \cdot in \cdot \sqrt{B}$; the thermal noise of the feedback resistor is $V_{R_F} = R_F \cdot \sqrt{\frac{4kTB}{R_F}}$.

The sensitivity of the sensor is S , and the power of the incident light is P . After the signal of the photoelectric sensor passes through the detection circuit, the output voltage is

$$V_O = I_O R_F = SP R_F. \quad (12)$$

The SNR of the whole detection circuit is

$$SNR = \frac{V_O}{V_n} = \frac{SP R_F}{\sqrt{B \cdot [R_F^2 \cdot (\omega_1 + \omega_2)]}}. \quad (13)$$

$$\omega_1 = \frac{4kT}{R_{ie}} + 2q \cdot (I_O + I_D) + in^2 \quad (14)$$

$$\omega_2 = 4kT R_F + (1 + \frac{R_F}{R_{ie}})^2 \cdot en^2 \quad (15)$$

For a given amplifier, its parameters of en and in are fixed values, so the SNR of the whole detection circuit is mainly affected by I_O , I_D , R_F , B .

3.2.1 Bandwidth of the circuit

From (11), we can see that the SNR and the bandwidth of the circuit have a great relationship. When all the electrical parameters (en , in , I_O , I_D , R_F) in the circuit are constant, (16) is established.

$$SNR \propto \frac{1}{\sqrt{B}} \quad (16)$$

It shows that the bandwidth is not the bigger the better. However, with the raising of the SNR, the bandwidth will decrease, and the waveform of the laser pulse signal will be influenced. Accordingly, both SNR and the high-frequency component of the signal should be considered. Generally, the laser pulse is a Gaussian pulse, which is the quasi-rectangular pulse. While the bandwidth of the amplifier influences the response of the amplifier to the quasi-rectangular pulse [30].

If the $\Delta f \cdot \tau = 0.5$ is met for the rectangular pulse, (Δf is the -3 dB bandwidth of the amplifier, τ is the rise time of the photoelectric conversion circuit), the ratio of the output pulse peak power and noise power is the largest, so the maximal SNR can be obtained [30].

The rise time of the 2-D photosensor is $1.5 \mu s$. In order to match the performance of the detector reasonably, the -3 dB bandwidth of the detection circuit should be around 330 KHz.

3.2.2 Photocurrent and feedback resistance

To analyze the influence of photocurrent I_O on the SNR, the influence of dark current I_D on the noise should be firstly considered. According to the principle of photoelectric detection, the dark current does not largely influence the SNR within the scope of possible changes. This is because the photocurrent is far greater than the dark current. However, when the photocurrent is weak (when the dark current and the photocurrent are comparable, such as in the presence of strong background light, the signal produced from the background light can be regarded as dark current), the influence of dark current will be aggravated. Thus the influence of the dark current cannot be ignored now.

When the situation of weak photocurrent is not considered, the dark current is regarded as a constant (maximum) $I_D = 500$ nA. Fig. 7 shows the relation of SNR with photocurrent I_O and feedback resistance R_F . It is observed that the photocurrent and resistance of feedback resistor all produce a large effect on the SNR from Fig. 7(a). Fig. 7(b) is the situation when azimuth is equal to 0 and elevation is equal to 0 in Fig. 7(a). It is observed that no matter how large the R_F of the feedback resistor is, the photocurrent produces more influence on the SNR of the measuring

circuit. Nevertheless, smaller R_F values decrease this influence. Fig. 7(c) is the situation when azimuth is equal to 90 and elevation is equal to 0 in Fig. 7(a). Fig. 7(d) is the SNR curve with the changes of feedback resistance after the photocurrent value is discretized. It shows that when the photocurrent value is constant, increasing the value of R_F of the feedback resistor properly can contribute to improving the signal-noise and raising the amplifier gain.

(a) Relationship between SNR, feedback resistance and photocurrent

(b) Relationship between SNR and photocurrent

(c) Relationship between SNR and feedback resistance

(d) Abscissa zoom of the relationship between SNR and feedback resistance

Fig. 7 Relationship between SNR, feedback resistance and photocurrent

3.3 Design of detection circuit

The above analysis and calculation show that an amplifier with low voltage noise under the high feedback is needed. To meet the above requirement, the trans-impedance amplifier (TIA) is adopted, while the uncompensated op amplifier (DOA) is selected for higher bandwidth.

The stray capacitance C_S that exists will form a zero with the feedback resistor R_F on the gain curve (Z_1 in Fig. 8), resulting in the approximation velocity at the intersection between the open-loop gain curve and noise gain curve of the operational amplifier approaching -40 dB/dec. The result of intersection is that the instability of the operational amplifier will cause self-excited oscillation. Thus, to eliminate the self-excited oscillation of the circuit, usually a feedback capacitance C_F is added for compensation, and a pole is introduced into the curve, with the compensated curve as shown in Fig. 8.

Fig. 8 Compensated Bode diagram

According to Fig. 8, to make the op amplifier to operate stably and reach the widest 2-order Butterworth frequency response, the value of feedback capacitance C_F is set as follows:

$$\frac{1}{C_F} = \sqrt{\frac{\pi \cdot GBP \cdot R_F}{C_S}}. \quad (17)$$

When the target scattering distribution is the Lambert reflector, it is easy to calculate the photocurrent I_o of echo power [31] in the starting phase of terminal guidance to be 1.1×10^{-5} A. The DOA adopts OPA657, whose electric parameters are $i_n = 1.3 \text{ f A/Hz}^{1/2}$, $e_n = 4.8 \text{ n V/Hz}^{1/2}$. The change curve of noise and SNR with the change of feedback resistance R_F is shown in Fig. 9 according to (4) and (6).

In the real application, although the SNR increases with the increase of feedback resistance, the fact is that not larger feedback resistance is better. On the one hand, the increase of feedback resistance will increase the noise of

circuit. On the other hand, the increase of feedback resistance is difficult to guarantee the resistance of four channels of resistors matched to equal.

Fig. 9 SNR and noise with feedback resistor

The resistor with high resistance has poor stability. Thus, the resistance of feedback (R_F) resistor is set as 100–300 k Ω .

According to the requirement on the correction precision, the SNR of circuit should be up to 53 dB. Besides, the linear range of applicability of ADC devices on the rear

end needs to be taken into consideration. And to prevent the system's dynamic range from being exceeded due to sudden increase of echo signal amplitude, the noise of circuit is $V_{Noise} = 3.3$ mV and SNR = 56 dB when the resistance of the feedback resistor is 300 k Ω in the maximum conditions. In this situation, the requirements on correction precision can be met.

According to the above analysis, the schematic diagram and parameters for the final detection circuit are made, as shown in Fig. 10. In the figure, C_2 is the junction capacitance of sensor, and R_3 and C_3 are the form of resistance capacitance (RC) filter circuit.

Fig. 10 Schematic diagram of detection circuit

The transfer function of signal extraction:

$$\frac{U}{I} = -\frac{1}{\frac{R_1 \cdot C_1 + R_2 \cdot C_2}{R_1 \cdot R_2 \cdot C_1} + j \left(\frac{1}{R_1 \cdot R_2 \cdot C_1} \cdot \frac{w}{w_0} - C_2 \cdot \frac{w}{w_0} \right)} \quad (18)$$

with

$$w_0 = \frac{1}{R_1 \cdot R_2 \cdot C_1 \cdot C_2}. \quad (19)$$

Amplitude-frequency characteristics:

$$F = -\frac{1}{\left(\frac{R_1 \cdot C_1 + R_2 \cdot C_2}{R_1 \cdot R_2 \cdot C_1} \right)^2 + \left(\frac{1}{R_1 \cdot R_2 \cdot C_1} \cdot \frac{w}{w_0} - C_2 \cdot \frac{w}{w_0} \right)^2} \quad (20)$$

Phase-frequency characteristic:

$$\phi_F = \tan^{-1} \frac{R_0 \cdot \frac{w}{w_0} - C_2 \cdot \frac{w}{w_0}}{\frac{R_1 \cdot C_1 + R_2 \cdot C_2}{R_1 \cdot R_2 \cdot C_1}} \quad (21)$$

with

$$R_0 = \frac{1}{R_1 \cdot R_2 \cdot C_1}$$

At resonance, the center frequency is

$$f = \frac{1}{2\pi \cdot \sqrt{R_1 \cdot R_2 \cdot C_1 \cdot C_2}}. \quad (22)$$

When adapting the parameters, it is required to guarantee the frequency of the input coding laser light source is near the center frequency. What's more, the phase margin of the front end circuit should be considered to prevent the self-excited oscillation of circuit.

Then simulation is conducted using Texas Instruments (TI) spice-based analog simulation program (TINA) of TI, with result as shown in Fig. 11, which shows the circuit is stable and has no overshooting. The actual circuit is built, and the PSD output signal is connected to the sensor signal extraction circuit to measure the output waveform, as

shown by the yellow line for channel one in Fig. 12 in details.

Fig. 11 Simulation results from TINA

Fig. 12 The output waveform from actual circuit

4. Experimental results and analysis

To verify the proposed method, the laboratory experiment environment is built, shown in Fig. 13 in details.

Fig. 13 Laser semi-active diffuse reflection experiment

The printed circuit board (PCB) was made according to the above analysis. In the laboratory, the laser was irradiated to the diffused reflection screen.

The inner axle, center axle and outer axle of the three-axle table were adjusted to enable the seeker of the three-axle table to receive the diffused reflection signal of the laser. The distance travelled by the laser beam was adjusted to make the photocurrent produced by the seeker about 0.01 mA and the data of the four channels was acquired using the digital acquisition card. The parameters of four channels are shown in Table 1.

Table 1 Experimental parameters table

Channel	Parameter	
	CF/pF	RF/k Ω
ONE	2.2	20
TWO	7.5	50
THREE	43	300
FOUR	50	350

Each power supply was turned on for data acquisition. The position of the laser was changed every time after data acquisition. The waveform of four channels is shown in Fig. 14.

Fig. 14 Four wave signals of detection circuit

The data is subjected to fast Fourier transformation (FFT) processing in matlab. Firstly, the frequency represented by a certain point n is calculated according to the result of processing: $F_n = (n - 1) \cdot F_s / N$. F_s is the frequency of sampling; N is the number of sampling sites. The first point represents the direct current (DC) component (i.e., 0 Hz). The presence of the DC component is mainly caused by the environmental factors such as stray light and the noise in the system. Thus, during the process of calculating the coordinate of the spot point, the first step is that the module value of the first point is divided by N and the DC component is obtained. Then according to the equation $n = F_n \cdot N / F_s + 1$, the module value with the specific frequency is calculated, while the result should be divided by $N/2$ to obtain the peak value of the original signal, with the result shown in Table 2.

In the process of data processing, the table only selects one channel of signals for processing each time, which can make the change trend of the noise easily seen. From the data of each channel, it can be seen that the trend of the influence of feedback resistance on the SNR ratio of the circuit and it is similar as shown in Fig. 9 in details.

Table 2 Experimental results table

Times	Noise/mV			
	First channel	Second channel	Thrid channel	Fourth channel
1	0.568	1.421	8.525	9.646
2	1.572	2.443	9.512	10.623
3	1.684	2.632	9.617	10.752
4	2.243	3.250	10.248	11.567
5	2.470	3.531	10.460	11.787

Times	Peak value/V (SNR/dB)			
	First channel	Second channel	Thrid channel	Fourth channel
1	0.185 (50.2)	0.694 (53.7)	4.312 (54.1)	4.890 (54.1)
2	0.503 (50.1)	1.178 (53.6)	4.752 (53.9)	4.997 (53.5)
3	0.519 (49.7)	1.224 (53.3)	4.664 (53.7)	4.997 (53.3)
4	0.628 (48.9)	1.430 (52.8)	4.733 (53.3)	4.997 (52.7)
5	0.689 (48.9)	1.557 (52.8)	4.827 (53.3)	4.997 (52.7)

It is observed from Table 2 that with the increase of testing times, the noise takes on an uptrend, and is obviously larger than the theoretical value, while the SNR is decreased. The possible reasons are as follows: (i) with the increase of the working time of the circuit, the thermal noise and the temperature drift will influence the noise of the circuit; (ii) with the increase of the working time of the laser device, its efficiency will be lowered, and light intensity will be weakened; (iii) the influence of the background light will also increase the noise of the circuit; (iv) the layout of circuit and signal integrity (SI), etc. may also lead to increased noise. Despite of the increase of noise by several times, the SNR is not largely decreased. Paying attention to eliminating the stray light in designing the optical lens and solving the problems causing noise in designing the circuit can further reduce the noise and raise the SNR of the photoelectric detection circuit.

5. Conclusions

This paper firstly analyzes the imaging characteristics of the imaging face of the photosensor according to the trajectory information and the characteristics of correction projectile based on the laser seeker. Then the relation between the resolution of the rolling angle and the resolution of the spot point position is resolved. Finally, the detection circuit with the resolution errors of the rolling angle as the major parameter is designed. The experiment verification shows that this design can meet the requirement on the resolution error of the rolling angle in the semi-active laser seeker. In addition, for the laser seeker signal, the SNR of the circuit serves as the dominating influencing factor for the reso-

lution error of the position. Actually, the fact is that not the larger the SNR is better. Therefore, by referring to the rolling angle resolution error and the transmission model of laser in the atmosphere, the satisfactory circuit can be easily designed. Considering the wide application areas of the photoelectric detection sensor in the semi-active laser weaponry in the future, the idea of this design can be taken as reference. Combined with the application of the photoelectric detection sensor in the related domains, its application value will be further improved.

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