Linearity of quadrant avalanche photodiode in laser tracking system

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The tracking precision of laser tracking system is affected by the angular resolution of quadrant avalanche photodiode. According to the detecting principle of quadrant avalanche photodiode, the light spot area, the optical intensity distribution, the non-uniformity of response, and the signal-to-noise ratio (SNR) that affect the linearity of the detector are studied. The light optical spot area and the optical intensity distribution can be adjusted through software. The non-uniformity of response and the SNR are influenced by the noise of the detector. Because the noise is affected by the optical intensity of the incident laser, it is difficult to obtain the law of the linearity caused by noise. When the light spot area and the optical intensity distribution are fixed, the other factors can be measured. With the detector scanned in raster scanning mode, the non-uniformity of response is measured at different SNRs. The linearity of detector is measured by a moving target that can reflect the illuminating laser to the detector in diffuse reflection mode. The nonlinear error of the linearity of detector can be minimized by increasing the SNR.

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Recently, the quadrant avalanche photodiode[1−5] has been the key device of laser tracking system. The goodness of fit that the output signal curve accords with the fitted line is called the linearity of quadrant avalanche photodiode. The research is mainly focused on the geometrical factor and the non-uniformity of response that affect the linearity of quadrant avalanche photodiode. The geometrical relationship between the error signal and eccentricity of light spot in the photosensitive area of the detector was analyzed[6,7]. The relationship between the non-uniformity of response and the linearity of the detector was also studied[8]. The influence of the bias voltage on the gain of the detector was investigated[9,10]. At the same time, the method of minimizing the nonlinear error by adjusting the bias voltage of the detector was put forward too. It was proposed that the nonlinear error could be minimized by introducing a correction factor[11−14]. But the main factors affecting the linearity of detector have not been completely studied yet.

In this letter, the main factors affecting the linearity of the detector are analyzed. The non-uniformity of response of quadrants and the linearity of the detector is measured. We propose the method to minimize the nonlinearity by increasing the signal-to-noise ratio (SNR). The results are important for improving the angular resolution and tracking precision of laser tracking systems.

When the center of light spot in the photosensitive detector area (whose radius is R) changes, the current of every quadrant will be different. The angular error signal can be obtained by difference method when the quadrant avalanche photodiode is applied to measure the angular error. The angular error can be written as

$$E_x = \frac{2}{\pi}\left(\frac{x}{r}\sqrt{1-\left(\frac{x}{r}\right)^2} + \arcsin\frac{x}{r}\right), \qquad (1)$$

where x is the eccentricity of the spot center in the X-direction, r is the radius of the light spot.

The change rate of the angular error, S_x, is obtained by the derivation of Eq. (1):

$$S_x = \frac{\mathrm{d}E_x}{\mathrm{d}x} = \frac{2}{\pi}\left(\frac{1}{r}\sqrt{1-\left(\frac{x}{r}\right)^2} - \frac{x^2}{r^3\sqrt{1-(x/r)^2}} + \frac{1}{r\sqrt{1-(x/r)^2}}\right). \qquad (2)$$

The linearity of the detector is obtained as the maximal deviation of the output signal curve from the fitted line within the full measuring range. Figure 1 shows the linearity of the detector in the direction of X.

The factors that affect the linearity of the detector are the size of the light spot in the photosensitive area, the optical intensity distribution, the incident laser power, the temperature, and the SNR.

When the radius of the light spot r is bigger than that of the photosensitive area R, part of the light spot cannot

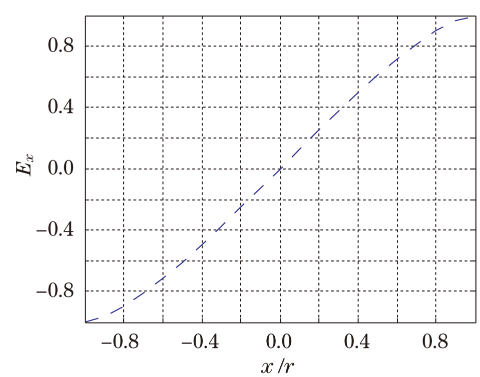

Fig. 1. Linearity of detector.

enter the photosensitive area, and the detecting precision decreases subsequently. When the radius of light spot is small, the blind area of the cross channel between quadrants causes the value of signal to be small. Sometimes the spot is on one of the quadrants and the precision of detector also decreases. From Fig. 2, as the radius of the light spot becomes smaller, the nonlinear error becomes larger. As the radius of the light spot becomes bigger, the detecting area becomes smaller. Usually we set

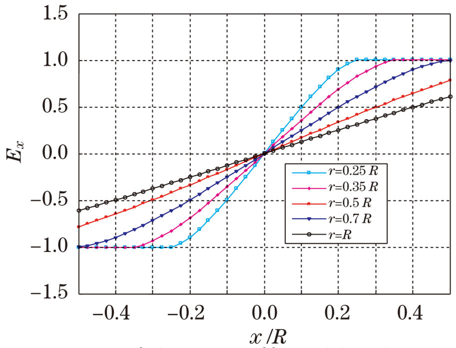

Fig. 2. Linearity of detector affected by the spot area.

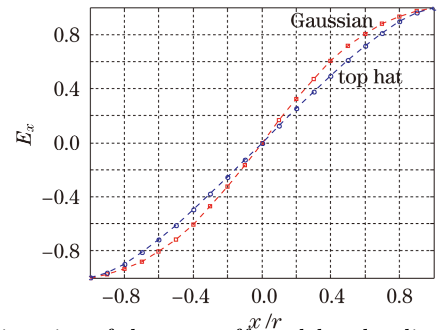

Fig. 3. Linearity of detector affected by the distribution of optical intensity.

r=0.5R, which can ensure the detecting area and at the same time reduce the nonlinear error caused by the light spot.

When x/r is fixed, the position of the light spot in the detector is invariable. The optical intensity distribution is in Gaussian mode, the expressions of the angular error signal by difference method will be changed. For the Gaussian distribution of $e^{-2(x^2+y^2)}$, we have (when r=0.5R)[14]

$$E_x = \frac{\int_0^{r+a} dx \int_0^{\sqrt{r^2-(x-a)^2}} e^{-2\left(x^2+y^2\right)} dy - \int_{a-r}^{0} dx \int_0^{\sqrt{r^2-(x-a)^2}} e^{-2\left(x^2+y^2\right)} dy}{\int_0^{r+a} dx \int_0^{\sqrt{r^2-(x-a)^2}} e^{-2(x^2+y^2)} dy + \int_{a-r}^{0} dx \int_0^{\sqrt{r^2-(x-a)^2}} e^{-2(x^2+y^2)} dy}, \quad (3)$$

where we use a to represent the eccentricity of the light spot in the X-direction in the photosensitive area. From Fig. 3, when the optical intensity shows a top hat distribution, the nonlinearity error is smaller than the one of Gaussian distribution.

The non-uniformity of response contains the non-uniformity of the response of every quadrant and that for different positions in the same quadrant[8]. When the non-uniformity of the response of every quadrant is different, the relationship between the output error signal and the eccentricity of the light spot in the photosensitive area is

$$E_x = \frac{\left[(\rho_1+\rho_2+\rho_3+\rho_4)\left\{\arccos\frac{x}{r} - \frac{x}{r}\sqrt{1-\left(\frac{x}{r}\right)^2} - (\rho_1+\rho_2)\pi\right\}\right]}{\left[(\rho_1+\rho_4-\rho_3-\rho_2)\left\{\arccos\frac{x}{r} - \frac{x}{r}\sqrt{1-\left(\frac{x}{r}\right)^2} + (\rho_1+\rho_2)\pi\right\}\right]}, \quad (4)$$

where ρ_1, ρ_2, ρ_3, and ρ_4 are the responses of the four quadrants. From Fig. 4, when the non-uniformity of response of every quadrant is larger, the nonlinearity error becomes larger and the deviation of zero point (when x=0, the value of E_x is the one of zero point) is larger accordingly.

The noise of the detector includes the shot noise, thermal noise, and the noise caused by the dark current. These noises belong to white noise and add upon the signal. The noise changes due to the variation of the received laser power. The noise would fluctuate due to the change of the signal, the angular error signal obtained by difference method would fluctuate. When the received laser power becomes bigger, the SNR is bigger, the fluctuant noise compared with the error signal becomes smaller and the nonlinear error is smaller too.

As the optical intensity of the incident laser power is high, one quadrant or some quadrants would be in the

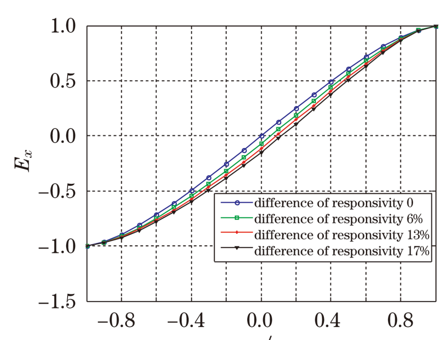

Fig. 4. Linearity of detector affected by the non-uniformity of response.

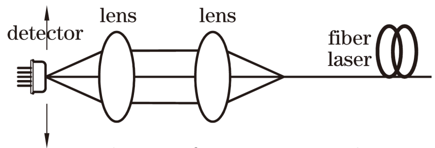

Fig. 5. Experimental setup for measuring the non-uniformity of response.

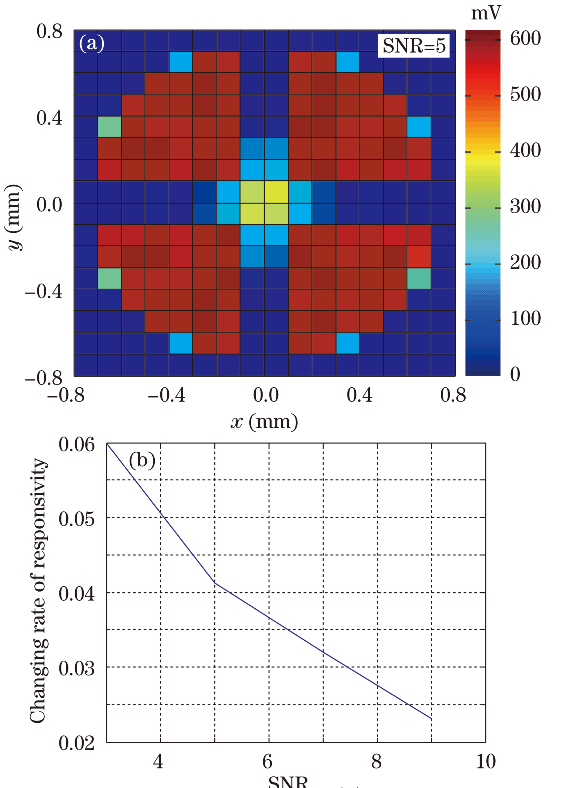

Fig. 6. Non-uniformity of response. (a) Distributing figure of response at SNR=5; (b) non-uniformity of response affected by SNR.

saturated state. The gain of the detector changes according to the change of temperature, linearity, and SNR.

The nonlinear error caused by the geometrical factors of the spot size and the distributing characteristics of optical intensity could be modified by introducing a correction factor in the circuit. However, the nonlinear error caused by SNR and the non-uniformity of the response cannot be modified in this way, as the SNR and the non-uniformity of the response are caused by the noise. We measured the linearity of the detector and the value of the non-uniformity of the response. In the experiment, r=0.5R and a top hat optical intensity distribution were used in order to minimize the affection of geometrical factors.

The detector was the NO. C30927E-01A0831 produced in EG&G company and was randomly selected from a batch of quadrant avalanche photodiodes. The diameter of the photosensitive area was 1.52 mm, the blind area of the cross channel between quadrants was 50−200 μm, the signal processing circuit was used to transform the current signal of the detector to voltage signal and to amplify the signal. The experimental setup is shown in Fig. 5. The diameter of fiber which produced 1064-nm laser was 100 μm and the output laser spot was focused to a diameter of 100 μm by a lens group. The laser power stability was 99%. The light spot scanned the detector by a 16×16 matrix without overlapping by moving the detector. The transformed voltage of the detector of every sub-region was measured under the same incident laser power. Figure 6(a) shows the measured response distribution. When the light spot scans the detector, the non-uniformity of the transformed voltage is

$$\eta = V_{\max} - V_{\min}/V_s, \tag{5}$$

where $V_{\max}$, $V_{\min}$, and V_s are the maximum, minimum, and average voltage in the detector.

The non-uniformity of response can be obtained by Eq. (5). Because the photosensitive area has the blind area and the scanning spot is round in shape, some sub-regions in the margin of the detector cannot be considered. The output laser power can be adjusted by adding an attenuator in the optical path. The non-uniformity of response can be measured at the different SNRs, as shown in Fig. 6(b). From the figure, we can conclude that because the difference of the materials of the detector is very small, the non-uniformity of response is small. Furthermore, when the SNR becomes bigger, the fluctuant value of signal within the signal becomes smaller, and the non-uniformity of response is smaller accordingly.

We measured the linearity of detector using the setup in Fig. 7. The sending axis of the illuminating laser and the receiving axis of the telescope of tracking system are coaxial. Cassegrain telescope was used in the tracking system. The effective focusing length was f. The laser illuminated the non-cooperative target by the mirror that was behind the secondary mirror of the telescope. The non-cooperative target was in the diffuse reflection. The detector placed at the front of focal point received the echo to measure the angular error. The radius of the light spot on the detector was 0.4 mm. The radius of photosensitive area was 0.76 mm. The moving range of the spot was from −0.17 to 0.17 mm. E_x changed from −0.425 to 0.425. The field of view was 2 mrad. The divergence angle of the illuminating laser was 1.2 mrad, the laser wavelengh was 1064 nm, and the frequency of the laser was 50 Hz. The diameter of the target was 1/6 of that of the laser beam. The linearity of the detector in the area of the laser beam was measured. E_x in this area was from −0.3 to 0.3. The relationship

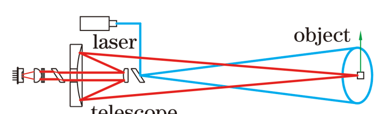

Fig. 7. Setup for measuring the linearity of detector.

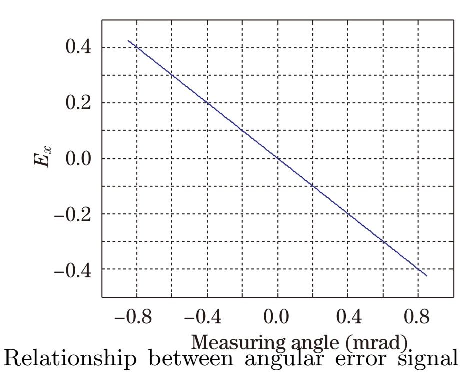

Fig. 8. Relationship between angular error signal and measuring angle.

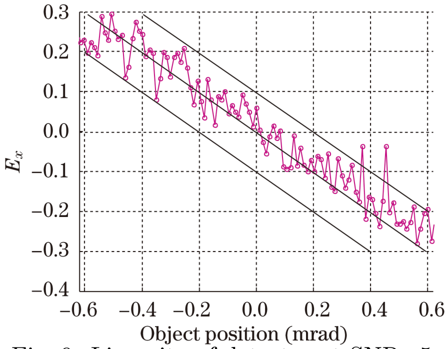

Fig. 9. Linearity of detector at SNR=5.

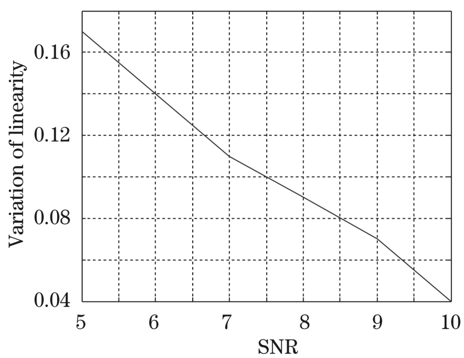

Fig. 10. Linearity of detector affected by SNR.

between the angular error signal and the measuring angle is

$$\varepsilon = rE_x/f. \tag{6}$$

Using Eq. (6), we obtain the result shown in Fig. 8.

In the experiment, the distance between the target and the detector was 50 m. At this place the diameter of optical spot of the illuminating laser beam was 60 mm. The target moved from one side to the other side of the illuminating laser beam in the uniform velocity, the target was set on a moving stage, the moving precision of the stage was 100 μm. The speed of the target was 1 mm/s. The detector gathered one data set every 20 ms (laser pulse period). The output laser power was adjusted to measure the linearity of the detector at different SNRs. The experiment result of SNR=5 is shown in Fig. 9. In this figure, the relationship between the angular error signal and the position of the target in the illuminating laser beam accords with that in Fig. 8.

The nonlinear error is given by

$$\delta = \Delta L_{\max}/x_{\mathrm{FS}}, \tag{7}$$

where $\Delta L_{\max}$ is the largest deviation between the curve of output signal and the fitted line, x_{FS} is the full measuring range. x_{FS} was fixed at 1.2 in the experiment. The linearity of the detector at different SNRs was measured by changing the illuminating laser power. With the nonlinear error calculated by Eq. (7) and shown in Fig. 10, the law of the nonlinearity error of the detector can be obtained.

From Fig. 9, the output signal of the detector is found to be fluctuant, so is the linearity curve. From Fig. 10, we can see that as the SNR becomes bigger, the noise is smaller, and the nonlinearity error of the linearity of the detector becomes smaller accordingly.

The white noise of the detector is the main factor that affects the linearity. When the light spot area and the optical intensity distribution are fixed, to increase the SNR is the main method to minimize the nonlinear error of the detector. The fluctuation of the signal is caused by the white noise and the instable laser power. It can be minimized by computing the even value of the signal. The affection of the noise of the signal processing circuit can also be considered.

In conclusion, the light spot area, the optical intensity distribution, the non-uniformity of response, and the SNR of the detector are researched. With the spot area and the distribution of the optical intensity fixed, the detector is scanned by the laser. The non-uniformity of response is measured at different SNRs. The linearity of detector is measured at different SNRs by a moving target in diffuse reflection mode. The nonlinear error of the detector can be minimized by increasing the SNR.

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