Sensors & Transducers, Vol. 25, Special Issue, December 2013, pp. 52-57

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The Study on the Method of Eliminating Errors of PSD

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Received: 16 September 2013 /Accepted: 15 October 2013 /Published: 23 December 2013

Abstract: PSD is a unique kind of semiconductor photoelectric position sensors. In this paper, the principle of PSD is introduced, and the relationship between coordinates position of the dot of laser beam and conversion formula is derived theoretically. The paper analyses the influence to PSD of external environment such as background light, reverse biased voltage and temperature, and the testing error of the non-linearity of PSD. At the end, the method of eliminating the testing error was put forword. *Copyright © 2013 IFSA.*

Keywords: PSD, Testing error; Non-linearity, Background light, Reverse biased voltage, Temperature.

1. Introduction

Position sensitive detector (PSD) is a kind of semiconductor photoelectric [1], which can measure the position of the incident light pot on the photosensitive surface continuously and accurately. The device has many advantages, such as small size, fast responding speed, high sensitivity, large linear range, low noise and simple subsequent circuit processing. After measured by the error correction and the compensation of optical path or circuit, the device is widely used in all kinds of vibration displacement measurements.

2. Principles

PSD is generally made by the P+IN structure, and it has the similar advantage of photodiodes, that is the photoelectric conversion efficiency, the sensitivity and the responding speed are better because of the thick I area. The working principle of PSD is based on the lateral photoelectric effect. As shown in Fig. 1(a), the P+ is both the photosurface and a uniform layer of resistive film, and the signal output electrode can be found on both sides of P+ layer. The I layer is in the middle and the common electrode which is in the lower layer is used to add reverse bias voltage. When there is an incident light on the photosurface, electric charges are generated. Due to the transverse electric field which parallels to the junction surface, the photocurrents I_1 and I_2 that flowing the electrodes at both ends are carried by the photon-generated carrier. Total current I_0 is equal to the sum of I_1 and I_2. Since the area resistance of PSD is uniform and the values of R_1 and R_2 are much larger than the load resistance R_L, the values of resistance R_1, R_2 only depend on the position of the incident current, such that [2]:

$$\frac{I_1}{I_2} = \frac{R_1}{R_2} = \frac{L-x}{L+x}, \tag{1}$$

where L is the distance from the midpoint of PSD to the signal electrode; x is the distance from the incident light spot to the midpoint of PSD. $I_0 = I_1 + I_2$ and (1) are combined such that

Article number P_SI_440

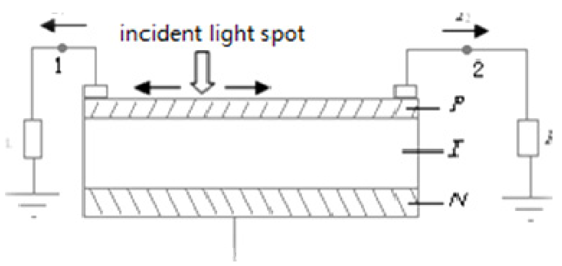
$$I_1 = I_0 \frac{L - x}{2L}, \quad (2)$$

$$I_2 = I_0 \frac{L + x}{2L}. \quad (3)$$

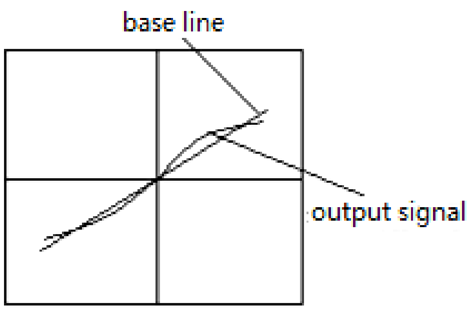
It can be seen that when the position of incident light spot is certain, the output current of signal electrode is proportional to the intensity of incident light. However, when the intensity of incident light is certain, the relation between the output current of signal electrode and x which is the distance of the incident light spot and the midpoint of PSD is linear. If the two output currents of the signal electrode are processed as follows:

$$P_x = \frac{I_2 - I_1}{I_2 + I_1} = \frac{x}{L}, \quad (4)$$

a useful result can be obtained, which is P_x only relates to the light spot position x, but not to the incident light intensity I_0. The characteristic of output position is showed in Fig. 1(b).



(a)Principles of PSD



(b) Output characteristic of PSD

Fig. 1. The principle and out characteristic of PSD.

3. The Factors Causing Testing Error of PSD and the Method of Eliminating

As specific position sensitive detector, PSD has its own advantages, but is not without disadvantages. For example, the influence of background light and temperature is quite significant. Besides, PSD itself is non-linear. If the factors are not eliminated, the testing results will be greatly affected.

3.1. The Influence of Background Light

As mentioned previously, the output signal of PSD has nothing to do with the intensity of incident light spot and the size of light spot. Increasing the intensity of incident light is favorable to increase the signal-to-noise ratio, thus the position resolution is enhanced. However, the device will become saturated if the intensity of incident light is too high. The significant advantage, which is the position output only relates to "the center of gravity" of the incident light spot, but not to the size of light spot, brings great convenience to application. But it should be noticed that the closer the light spot moves towards the edge, the greater the error will be. In order to reduce the edge effect, the light spot should be small as possible and the center sensitive parts should be only used.

The intensity of the background light has an impact on the error of position output. The reason is that when the background light I is existing, (2) and (3) are changed to [3]:

$$I_1 = I_0 \frac{L - x}{2L} + I, \quad (5)$$

$$I_2 = I_0 \frac{L + x}{2L} + I. \quad (6)$$

After the process, the output position signal is written as

$$P_X = \frac{I_2 - I_1}{I_2 + I_1} = \frac{I_0}{2I + I_0} \times \frac{x}{L}. \quad (7)$$

It is obvious that the change of the intensity of the background light will influence the error of the position output.

There are two methods of eliminating the influence of the background light, which are the optical method and the electric method.

3.1.1. The Optical Method of Eliminating the Influence of the PSD Background Light

Light will be absorbed when it is transmitting in any substances. Most substance has the general property of matters - wavelength selectivity. That is defined as for different wavelengths of light, the absorption coefficients are different, even vary widely. Based on the property, the optical method of making optical frequency filter is putting a filter matching the signal light to filter out most of the background light.

Because the light from laser has the characteristic of high directivity, monochromaticity and good brightness, the semiconductor laser diodes are used by most light resources when testing. Since the wavelength of the laser is in a very narrow range, putting a narrowband filter matching the wavelength of laser could basically remove the effect of the background light.

Visible light is electromagnetic radiation which has a wavelength in the range of 380 nm to 780 nm. Different wavelengths cause different color visions. Visible light is classified into red, orange, yellow, green, indigo, blue and purple based on the wavelength and the red light has a wavelength of 622 nm-780 nm. The wavelength which is chosen by the sensor is about 650 nm and it is general from dotted red laser. Firelight has a large wavelength range, including UV-light (<380 nm), visible light (380 nm-780 nm) and infrared light (>780 nm).The interference of environment light and firelight can be reduced by the filer whose performance parameters are as follows: pass-band range is from 620 nm to 660 nm; transmittance of pass-band is above 80 %; stop-band range is 400 nm-620 nm and 660 nm - 800 nm; cut-off depth is 0.8 %.

3.1.2. The Electric Method of Eliminating the Influence of the PSD Background Light

In the electric method, impulse modulation is used for the light resource, and lock-in amplifying and synchronous detection is used for the output signal to filter the background light. Impulse modulation is a method that the magnitude of the pulse sequence changes with the signal. The impulse modulation signal can be describes as [4]:

$$S_{PAM}(t) = [A_0 + f(t)]S_p(t), \qquad (8)$$

where A_0 which represents the DC level is the constant. Message signal $f(t)$ is bipolar and its DC level is zero. The waveform of pulse sequence $S_p(t)$ can be arbitrary, normally the square wave is chosen. The impulse modulation signal is obtained by multiplying signal $[A_0 + f(t)]$ and $S_p(t)$. Assuming A is the magnitude of the square wave, τ is the width, and $T_s = 2\pi / \omega_s$ is the repetition period, only a low-pass filter is needed during the demodulation processing to obtain the signal spectrum near the zero frequency. The signal is the original signal $f(t)$.The demodulation processing is showed in Fig. 2, where $S_0(t) = \frac{A\tau}{T_s} f(t)$.

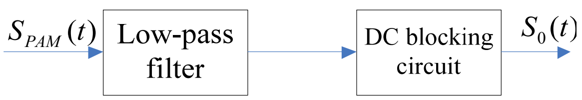


Fig. 2. The demodulation processing.

3.1.3. Experimental Results

Table 1 shows the experimental results of displacement-measuring system which is measured by the previous method of eliminating the influence of the PSD background light under different light intensity. In the experiment, the normalized displacement of the light spot on the PSD was 20 mm.

Table 1.theresults of the sensor output when the displacement of the light spot is 20 mm under different light intensity

No.	Initial value (mm)	Final value (mm)	Output (mm)	Avera -ge (mm)	Relati -ve error	Condi -tion
1	9.82	-10.1	19.92	19.99	0	Natural light indoor during the day
2	9.88	-10.1	19.98			
3	9.86	-10.2	20.06			
1	9.93	-10.3	20.23	20.22	1.1 %	Strong light indoor during the day
2	9.94	-10.2	20.14			
3	10	-10.3	20.3			
1	9.74	-10.2	19.94	19.92	0.4 %	No light indoor during the night
2	9.78	-10.2	19.98			
3	9.73	-10.1	19.83			
1	9.9	-10.4	20.3	20.26	1.3 %	Strong light indoor during the night
2	9.85	-10.4	20.25			
3	9.83	-10.4	20.23			
Ave				20.1		

According to Table 1, when the condition is natural light indoor during the day, the relative error is 0.05 %; when the condition is strong light indoor during the day, the relative error is 1.11 % (the ultra high brightness xenon search light used in the experiment is greatly brighter than sunlight and firelight); when the condition is no light indoor during the night, the relative error is 0.4 %; when the condition is strong light indoor during the night, the relative error is 1.3 %.

The experimental results shows that after the previous methods of eliminating the influence of the background light, the displacement-measuring system using PSD as sensor could meet requirements accurate measurement of displacements with the interference of strong light.

3.2. The Influence of Dark Current

For the photosensitive elements such as PSD, the dark current increases with increasing ambient temperature. Experiments indicate that the dark current of PSD increases by 1.15 times when the temperature increases 1 °C. In order to improve the sensitivity and the dynamic response, reverse voltage is commonly used. But the reverse voltage can cause the increase of dark current, so the measure precision will be influenced. Thus when studying the testing system based on PSD, the influence of dark current should be considered and eliminated as possible.

According to experiments, the current which is produced by the dark current is DC or slowly changing signal. In the case of the dark current existing, the current equals to the output signal plus a slowly changing voltage. So the dark current can be eliminated by designing the circuit as shown in Fig. 3.

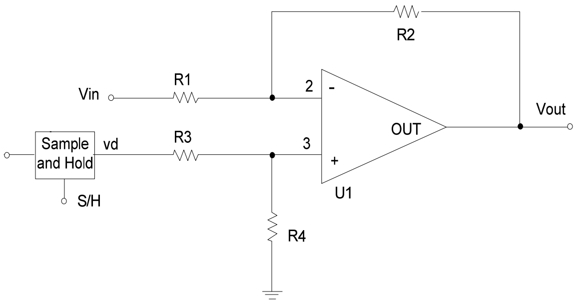


Fig. 3. The circuit of eliminating dark current.

Where V_d is the interference level of dark current; V_{in} is the output signal after adding the interference level.

$$R_1 = R_2 = R_3 = R_4 \tag{9}$$

$$V_o = -(V_{in} - V_d) \tag{10}$$

According to (10), the circuit realizes the function of eliminating background interference and dark current. Instead of amplified action, the circuit only inverse the signal.

3.3. The Non-linearity Error

Theory analysis and experimental results demonstrate that the non-linearity error of PSD is quite greater than the non-linearity error causing by the optical system and circuit. To improve the output property of PSD and the large-scale measurement accuracy, the non-linearity error correction of PSD is needed. Since the silicon wafer which is used to make PSD always presents a slow change of gradient, the position error function E(x, y) on the whole PSD surface is a small gradient surface. By the discretization of the function, a series of values of error function on the lattice gird are gained. For the values that are not on the gird, interpolation, neural network and other methods can be used to get the functional approximation. Thus the approximation value of the specific spot is obtained.

3.3.1. The Discretization of the Error Function

The non-linearity error of PSD is relatively independent in the directions of X and Y. for every spot on the photosurface, two error functions which are $E_x(x, y)$ in the direction of X and $E_y(x, y)$ in the direction of Y is existing. Since the derivation process of $E_x(X, Y)$ and $E_y(x, y)$ is similar, $E_x(X, Y)$ is taken as example. PSD is put on the high-precision displacement platform, and then the laser device is fixed to shine on the PSD photosurface. The control platform moves forward to the direction of X and Y as certain step length S, so the error functions $E_x(x_i, y_j)$ and $E_y(x_i, y_j)$ on the grid are obtained:

$$E_x(x_i, y_j) = x_i' - x_i'' \tag{11}$$

$$E_y(x_i, y_j) = y_j' - y_j'', \tag{12}$$

where (x_i' , y_j') is the output measurement of PSD on the grid; (x_i'' , y_j'') is the accurate position indication on the grid point.

3.3.2. Non-linear Compensation Method Based on Interpolation

On the photosurface of PSD, a series of discrete points form a rectangle grid. A rectangle area A_1 A_2 A_3 A_4 is chosen, the error function values of A_1 A_2 A_3 A_4 are, in order, $E_x(A_1)$, $E_x(A_2)$, $E_x(A_3)$, $E_x(A_4)$. Then the intent is to compute the interpolation function $E_x(x, y)$. (x, y) is the point in the rectangle area of A_1 A_2 A_3 A_4. Because the interpolation function has the message of four points, the coefficient function of the interpolation function can be described as 5]:

$$\phi_1(x, y) = a + bx + cy + dxy. \tag{13}$$

Then error function of any point (x, y) in the rectangle area is as follows:

$$E_x(x, y) = \sum_{i=1}^{4} E_x(A_i)\phi_i(x, y). \tag{14}$$

According to the error function and the output measurements of PSD, the actual position value can be obtained:

$$\begin{cases} X_R = X_{out} - E_x(x,y) \\ Y_R = Y_{out} - E_y(x,y) \end{cases}, \quad (15)$$

where X_R , Y_R are the actual position values, X_{out} , Y_{out} are the output measurements of PSD.

3.3.3. Experimental Results

In the static measurement, the input-output related curve which is called calibration curve is commonly obtained by the experimental methods. Most testing systems in practice are non-linear. On the condition that the degree of nonlinear term is not high and the change range of input is small, a reference line which is called fitting straight-line can be used to represent a part of the practical curve. Degree of nonlinearity is defined as the deviation of the calibration curve from the fitting straight-line. The percentage of the maximum of the deviation of the calibration curve from the fitting straight-line versus the nominal output range of system is as follows [6]:

$$\delta_L = \frac{(\Delta y_L)_{max}}{y_{FS}} \times 100\%, \quad (16)$$

$$(\Delta y_L)_{max} = \max\left|\Delta y_{iL}\right| \ (i = 1, 2, \cdots, n), \quad (17)$$

$$\Delta y_{iL} = \bar{y}_i - y_i, \quad (18)$$

where y_{FS} is the full scale output, and $y_{FS} = \left|B(x_{max} - x_{min})\right|$, B is the slope of the fitting straight-line; Δy_{iL} is the deviation of the average output of the point i from the corresponding point on the fitting straight-line; $(\Delta y_L)_{max}$ is the max deviation in the n points.

To obtain the degree of nonlinearity, the key is to gain the fitting straight-line. The degree of nonlinearity is different if the fitting straight-line is obtained by different methods. At present, there is no uniform standard for the fitting straight-line, two methods are commonly used, which are the base line and the least squares line. Here, the base line is used to replace input-output curve, the solving process relatively simple. If two endpoints $(x_1, \bar{y}_1)$, $(x_n, \bar{y}_n)$ are connected, the base line is

$$y = \bar{y}_1 + \frac{\bar{y}_n - \bar{y}_1}{x_n - x_1}(x - x_1). \quad (19)$$

Table 2 shows the testing results of PSD which are not measured by the non-linear compensation method. Table 3 shows the testing results of PSD which are measured by the non-linear compensation method.

Table 2. The testing results of PSD which are not measured by the non-linear compensation method.

Input displacement (mm)	Output displacement (mm)			
	No. 1	No. 2	No. 3	Average value
20.67	17.09	17.13	17.17	17.13
17.72	15.78	15.81	15.86	15.82
14.76	14.25	14.33	14.42	14.34
11.81	12.36	12.41	12.49	12.42
8.86	9.33	9.35	9.43	9.37
5.91	6.33	6.37	6.42	6.37
2.95	3.03	3.04	3.08	3.05
0.00	0.00	0.00	0.00	0.00
-2.95	-2.92	-2.90	-2.85	-2.89
-5.91	-5.85	-5.81	-5.81	-5.82
-8.86	-8.70	-8.69	-8.66	-8.68
-11.816	-11.04	-11.06	-11.05	-11.05
-14.766	-13.70	-13.70	-13.64	-13.68
-17.72	-16.45	-16.51	-16.45	-16.47
-20.67	-19.003	-18.95	-18.77	-18.92

Table 3. The testing results of PSD which are measured by the non-linear compensation method.

Input displacement (mm)	Output displacement (mm)			
	No. 1	No. 2	No. 3	Average value
35	34.58	34.99	35.56	35.04
30	29.76	29.95	30.3	30.00
25	24.91	25.13	25.09	25.04
20	19.91	20.14	20.1	20.05
15	14.97	15.02	15.13	15.04
10	10.09	9.92	9.97	9.99
5	4.85	4.85	4.89	4.86
0	-0.11	-0.12	0.14	-0.03
-5	-4.97	-5.1	-5.06	-5.04
-10	-10.15	-10.13	-10.06	-10.11
-15	-15.22	-15.09	-14.97	-15.09
-20	-20.62	-20.27	-20.15	-20.35
-25	-25.28	-25.11	-25.1	-25.16
-30	-30.69	-30.21	-30.36	-30.42
-35	-35.53	-36.21	-35.21	-35.65

According the results of Table 2 and Table 3, by (16), (17), (18), (19), the degree of nonlinearity is 6.38 % without the non-linear compensation, while it is 0.562 % after measured by the non-linear compensation.

The experimental results demonstrate that after measured by the non-linear compensation method, the test precision is greatly improved after measured by the non-linear compensation method and can meet the test requirements.

4. Conclusions

PSD is a kind of semiconductor photoelectric position sensors which is widely used. But many disadvantages need to be considered, such as the non-linear error of output and the influence of background light, reverse biased voltage and temperature. Thus when the testing system is designed, these factors need to be corrected and compensated by the methods of filtering circuit of dark current elimination, non-linearity correction and so on.

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