SCIENTIFIC PUBLICATIONS OF THE STATE UNIVERSITY OF NOVI PAZAR
SER. A: APPL. MATH. INFORM. AND MECH. vol. 5, 2 (2013), 85-92.

Sensitivity Analysis of a Position Device with Quadrant Photodiode

Ž. Barbarić

Abstract: A precise determination of laser beam position or laser illuminated object position using quadrant photodiode can be made in different arrangements signal processing. In this paper two arrangements for displacement signals processing are compared. New relationships of displacement signal using four (2+2) and only two (1+1) opposite sectors on quadrant photodiode are derived. Sensitivity of position sensitive devices with quadrant photodiode is analyzed.The sensitivity is higher for (1+1) than (2+2) configuration, for equal parameters. This is an important result in designing of the command and control devices in laser guidance systems

Keywords: Position sensitive detector, quadrant photodiode, displacement signal, sensitivity of device

1 Introduction

The principle of QPD positioning is simple. Incoming light is focused on the detector as a spot. Comparing of the output currents received from each of the four quadrants, the position of the spot on the surface can be determined. Thus, in general, photo-detection system can be functionally divided into two main parts: a sensing stage and a post-processing one. In the second one, the signal post-processing stage, the standard approach difference of the sum of signals coming from left- and right-side quadrant for horizontal and the difference of the sum of signals coming from upper- and down-side quadrants for vertical displacement (2+2). This research suggests a new relationship of displacement signal using two opposite sectors on a QPD. In a post-processing stage, through signal processing from two opposite sectors on QPD is named as novel arrangement or (1+1) configuration.

In a first combination, two and two sectors (2+2) are used [2], [3], in the second combination, only two sectors (1+1) are used [4] to obtained displacement signal. As it is known, a displacement signal is a function of the irradiance distribution on sensitive surface of photodiode [2]. Effects of the irradiance are analysed in[2]. Displacement signals are functions of linear combination of error function for Gaussian distribution. That is reason for sensitive analysis in the case of constant irradiance distribution.

Manuscript received December 14, 2012; accepted April 28, 2013.
Ž. Barbarić is with the State University of Novi Pazar, Novi Pazar, Serbia

In this paper the relations of displacement signal and sensitivity of a position sensitive detector for both configurations (1+1) and (2+2) are derived. Sensitivity as a function of displacement distance is analysed.

2 Displacement signals

Geometry of a quadrant photodiode with a laser spot centred at (x_0, y_0) is shown in Fig.1. Also, in Fig. 1 four segments and two coordinate systems are presented. Firstly, a constant irradiance distribution and constant laser beam spot of radius $r$are assumed.

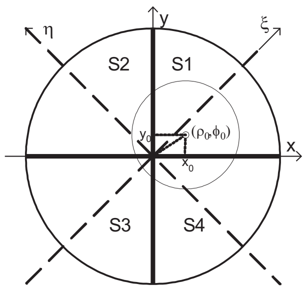

Fig. 1: A quadrant photodiode geometry

A direct measurement of displacements centre of spot x_0 and y_0 by processing signals from the quadrant photodiode is not possible. Having measured the signals, it is possible to determine the ratios of displacements and a light spot radius, e.g. $x_0/r$and y_0/r. For determining these relations for displacement signal, it is essential to know the irradiance distribution on the photodiode surface [2], [3].

If the irradiance on the photodiode surface is a constant one, then the optical power on sector is $P_k = E_0 A_k$, where E_0 represent the irradiance at the photodiode surface, and A_k is the area of the illuminated part of the k-th sector or quadrant of the photodiode (k=1,2,3,4). The optical power on sector and difference of the signal power is a function of the irradiance, laser power and atmosphere conditions, and the distance between a laser source and photodiode. These are reasons for normalization form of displacement signals.

The displacement signals along x and $y$axes are obtained from the difference of the signal received by the pair sectors. A normalized form of displacement signal for combination of four sectors (2+2), we can write [2] for $x$and$y$ orthogonal channels:

$$\varepsilon_x = \frac{(A_1(\rho_0,\phi_0)+A_4(\rho_0,\phi_0)) - (A_2(\rho_0,\phi_0)+A_3(\rho_0,\phi_0))}{(A_1(\rho_0,\phi_0)+A_4(\rho_0,\phi_0)) + (A_2(\rho_0,\phi_0)+A_3(\rho_0,\phi_0))}$$

$$\varepsilon_y = \frac{(A_1(\rho_0,\phi_0)+A_2(\rho_0,\phi_0)) - (A_3(\rho_0,\phi_0)+A_4(\rho_0,\phi_0))}{(A_1(\rho_0,\phi_0)+A_2(\rho_0,\phi_0)) + (A_3(\rho_0,\phi_0)+A_4(\rho_0,\phi_0))} \qquad (1)$$

The displacement signals along $\xi$and η axes are obtained from the difference of the signal received by the sectors S_1 and S_3, and S_2 and S_4, respectively. A normalized form of displacement signals for two sectors (1+1), we can write for ζ and η orthogonal channels [4]:

$$\varepsilon_{\xi}(\rho_0,\phi_0)=\frac{A_1(\rho_0,\phi_0)-A_3(\rho_0,\phi_0)}{A_1(\rho_0,\phi_0)+A_3(\rho_0,\phi_0)}$$

$$\varepsilon_{\eta}(\rho_0,\phi_0)=\frac{A_2(\rho_0,\phi_0)-A_4(\rho_0,\phi_0)}{A_2(\rho_0,\phi_0)+A_4(\rho_0,\phi_0)} \quad (2)$$

The normalized form of displacement signals in the combination (2+2), according to the Eq.(1), along x and $y$axes is obtained in the one

$$\varepsilon_x(\rho_0,\phi_0)=\frac{2}{\pi}\left(\frac{\rho_0}{r}\cos(\phi_0)\sqrt{1-(\frac{\rho_0}{r}\cos(\phi_0))^2}+a\sin(\frac{\rho_0}{r}\cos(\phi_0))\right)$$
$$\varepsilon_y(\rho_0,\phi_0)=\frac{2}{\pi}\left(\frac{\rho_0}{r}\sin(\phi_0)\sqrt{1-(\frac{\rho_0}{r}\sin(\phi_0))^2}+a\sin(\frac{\rho_0}{r}\sin(\phi_0))\right) \quad (3)$$

The normalized form of displacement signals in the combination (1+1), according to the Eq.(2) along ζ and η axes is obtained in the one

$$\varepsilon_{\zeta}(\upsilon_0,\phi_0)=\frac{\frac{\rho_0}{r}\cos(\phi_0)\sqrt{1-(\frac{\rho_0}{r}\cos(\phi_0))^2}+\frac{\rho_0}{r}\sin(\phi_0)\sqrt{1-(\frac{\rho_0}{r}\sin(\phi_0))^2}+a\sin(\frac{\rho_0}{r}\cos(\phi_0))+a\sin(\frac{\rho_0}{r}\sin(\phi_0))}{\frac{\pi}{2}+\frac{\rho_0^2}{r^2}\sin(2\phi_0)}$$

$$\varepsilon_{\eta}(\upsilon_0,\phi_0)=\frac{\frac{\rho_0}{r}\sin(\phi_0)\sqrt{1-(\frac{\rho_0}{r}\sin(\phi_0))^2}-\frac{\rho_0}{r}\cos(\phi_0)\sqrt{1-(\frac{\rho_0}{r}\cos(\phi_0))^2}+a\sin(\frac{\rho_0}{r}\sin(\phi_0))-a\sin(\frac{\rho_0}{r}\cos(\phi_0))}{\frac{\pi}{2}-\frac{\rho_0^2}{r^2}\sin(2\phi_0)} \quad (4)$$

The normalized displacement signals ε_x (3) and ε_{ζ} (4) in polar coordinates are shown in Fig.2. The normalized displacement signals depend on both parameters, the maximum displacement signal is always around axes for each value of ρ_0/r, as it is presented in Fig.2. Also, the normalized displacement signal increases with ρ_0/r, and the maximum value of displacement signal is obtained for ρ_0/r=1.

The normalized displacement signals ε_x (3) and ε_{ζ} (4) in the Cartesian coordinates are shown in Fig. 3. The normalized displacement signal ε_x (doted) in Fig. 3 is a function only to normalized displacement centres (x_0/r). Therefore, the normalized displacement signal ε_{ζ}, for two sectors (1+1), is a function of both x_0/r and y_0/r, as it is shown in Fig.3, for two values y_0/r. For other axes, the same result is obtained, as it is given in (3) and (4).

The normalized displacement signals ε_x and ε_y are dependent on only one coordinate, and can be used in a uncoupled laser tracking system. The normalized displacement signals ε_{ζ} and ε_{η} are dependent on both coordinates, and can be used in a coupled laser tracking system.

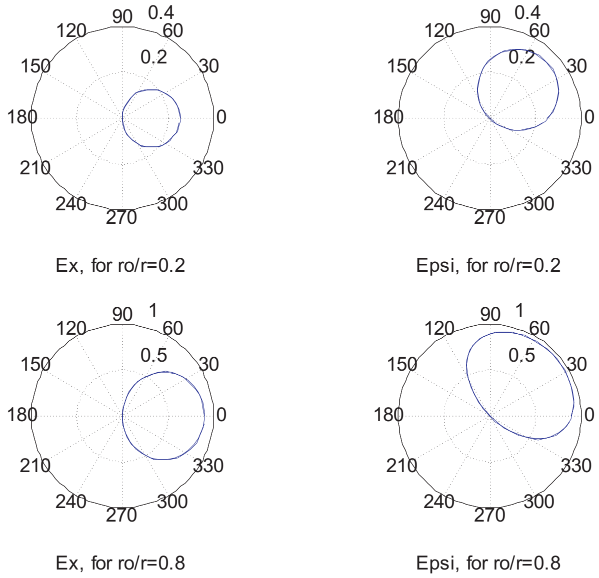

Fig. 2: The displacement signals ε_x and ε_ζ as a function ϕ_0, for ρ_0/r=0.2 and 0.8.

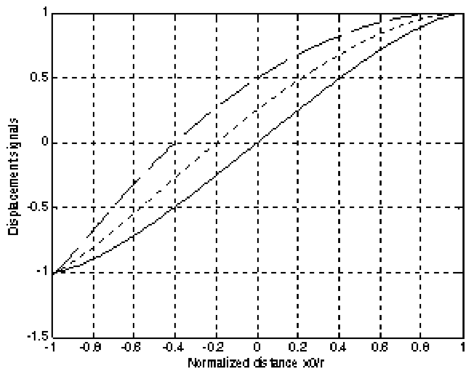

Fig. 3: The displacement signals $\varepsilon_x(-)$ and $\varepsilon_{\zeta,}$ for $y_0/r = 0.2$ $(\ldots)$ and 0.4 (–) as a function of the normalized distance x_0/r.

3 Sensitivity analysis

A sensitivity is defined as the first derivation of displacement signal respect to displacement distance centre of spot. The sensitivity for (2+2) configuration, from (3), it is derived

$$\frac{\delta\varepsilon_x(\rho_0,\phi_0)}{\delta\rho_0} = S_x = \frac{4}{\pi r}\cos(\phi_0)\sqrt{1-(\frac{\rho_0}{r}\cos(\phi_0))^2}$$

$$\frac{\delta\varepsilon_y(\rho_0,\phi_0)}{\delta\rho_0} = S_y = \frac{4}{\pi r}\sin(\phi_0)\sqrt{1-(\frac{\rho_0}{r}\sin(\phi_0))^2} \tag{5}$$

From (5), the sensitivity S_x tends to zero for ρ_0/r=1, and the sensitivity S_x has the maximal value around the centre of photodiode, where $S_{max}=4/(r\pi)$, ϕ_0=0. In Fig.4, the change of sensibility is shown as a function ρ_0/r .

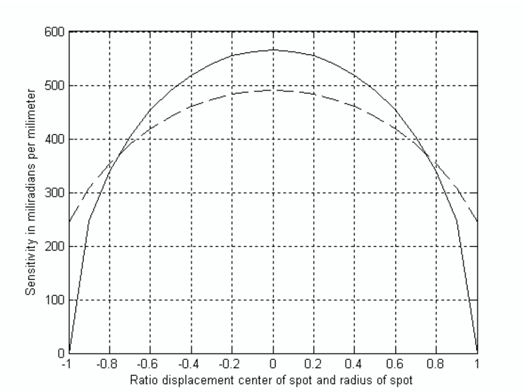

Fig. 4: The sensitivity S_x as a function of normalized distance ρ_0/r (r=2.25mm), for three values of ϕ_0=0, and π/6 (–)

The sensitivity S_x is changeable in respect to ρ_0/r and ϕ_0, as it is shown in Fig.4. The maximum value of the sensitivity is around the centre quadrant photodiode, ρ_0=0. The sensitivity increases when the angle ϕ_0 measured from x-axes decreases.

Also, from (5), the sensitivityS_x increases if the radius of spot decreases, for the constant ρ_0/r. In Fig. 5, the change of sensibility S_x (7) as a function radius of spot is presented.

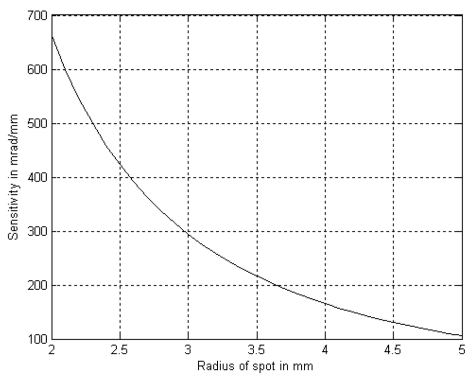

Fig. 5: The sensitivity S_x as a function radius of spot ρ_0/r=0.5 for $\phi_0 = \pi/4$.

A theoretical analysis of the quadrant photodiode sensitivity, where the Gaussian distribution of the light spot irradiance is given in [5]. The sensitivity was calculated for a full range of the ratio between the light spot radius and the photodiode radius. In this paper, it is shown that the sensitivity decrease, while the radius of spot increases.

The sensitivity for (1+1) configuration from (4) are derived from ε_ζ and $\varepsilon_\eta$displacement signals in the forms of

$$\frac{\delta\varepsilon_\zeta(\rho_0,\phi_0)}{\delta\rho_0} = S_\zeta = \frac{2}{r}\frac{\cos\phi_0\sqrt{1-\left(\frac{\rho_0}{r}\right)^2\cos^2\phi_0}+\sin\phi_0\sqrt{1-\left(\frac{\rho_0}{r}\right)^2\sin^2\phi_0}-\varepsilon_\zeta\frac{\rho_0}{r}\sin 2\phi_0}{\frac{\pi}{2}+\frac{\rho_0^2}{r^2}\sin 2\phi_0}$$
$$\frac{\delta\varepsilon_\eta(\rho_0,\phi_0)}{\delta\rho_0} = S_\eta = \frac{2}{r}\frac{\sin\phi_0\sqrt{1-\left(\frac{\rho_0}{r}\right)^2\sin^2\phi_0}-\cos\phi_0\sqrt{1-\left(\frac{\rho_0}{r}\right)^2\cos^2\phi_0}+\varepsilon_\eta\frac{\rho_0}{r}\sin 2\phi_0}{\frac{\pi}{2}-\frac{\rho_0^2}{r^2}\sin 2\phi_0} \tag{6}$$

We can see the sensitivity (6) becomes too complicated for the analysis. The change of sensitivity S_ζ is given in Fig.6.

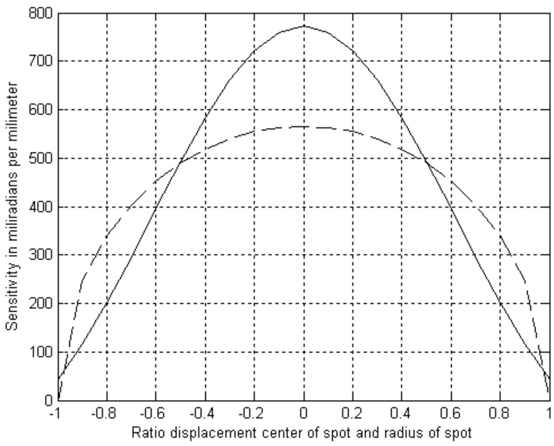

Fig. 6: The sensitivityS_ζ as function of normalized distance ρ_0/r (r=2.25mm), for two values ϕ_0=0, and π/6 (–)

The sensitivity is changeable in respect to ρ_0/r and ϕ_0, as it is shown in Fig.6. The maximum value of sensitivity is around the centre of quadrant photodiode, ρ_0=0. The sensitivity increases with the angle ϕ_0, the angle is measured from x-axes.

The ratio sensibility S_ζ and S_x as a function of angle ϕ_0, is shown in Fig.7.

The sensitivity ratio is higher than one for all range of angle ϕ_0, as it is shown in Fig.7. The sensitivity ratio increases respect to angle ϕ_0, and decreases with increases ρ_0/r.

The sensitivity is higher for (1+1) than (2+2) configuration, for the equal parameters, as it is shown in Fig.7. The similar results are obtained in [6], only around the centre of the quadrant photodiode. This is a significant result in designing command and control devices of laser guidance systems.

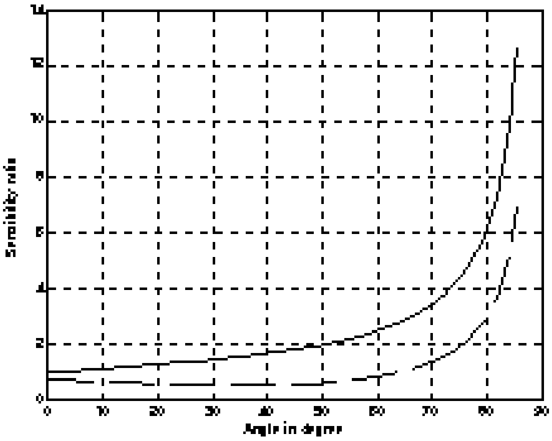

Fig. 7: The sensitivity ratio S_ζ and S_x as a function of angle ϕ_0, for $\rho_0/r = 0.2$(-), and 0.6(—) and $r = 2.25$mm.

4 Conclusion

The analysis of displacement signals shows that the normalized displacement signals ε_x and ε_y are independent, and can be used in the uncoupled laser tracking system, but the normalized displacement signals ε_ζ and ε_η are dependent, and can be used in the coupled laser tracking system.

The analysis of the sensitivity where the constant distribution of the light spot irradiance is assumed. The sensitivity is calculated for the full range of the ratio between the distance centre of light spot and the light spot radius. The sensitivity in (1+1) configuration is better than the sensitivity in (2+2) configuration. This result can be used in designing command and control devices of the laser guidance systems.

Acknowledgement

This paper has been partially supported by the Ministry of Education, Science, and Technologic Development the Republic of Serbia under Grant TR-32023.

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