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Impact of Stray Illumination Noise on the Position Response of Position-Sensitive Devices

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Abstract: Position-sensitive Devices (PSDs) are often used in the industrial environment, where the system light source used for position measurement is co-existing with many other light sources in the vicinity, along with their reflections and back-scatters from various surfaces. These unavoidable stray beams and illumination noises may fall on the detector surface in different spatial distributions and produce unpredicted variations in their position response. Some of the light sources may even have flying or rotating beams of sufficient energy. In this study, attempt was made to model and analyze these stray noises with respect to the operation of PSDs. Thus it was investigated how the presence of the spurious sources changes the behaviour of these detectors and how much is the position output modified quantitatively. The experimental results obtained by using PSDs and signal beams along with the spurious sources are presented. The obtained data is compared with the results from the proposed mathematical model to be within fraction of a percent of error.

Key words: Position-sensitive Detectors, background noise, lateral-effect detectors

INTRODUCTION

In the industry, telecommunication and other sectors, many applications require accurate measurement of displacement of objects through non-contact methods. Semiconductor Position-sensitive Detectors (PSDs) offer very good solutions for such applications and since their inception in late fifties, these devices have become a major tool for lateral position measurement[1]. Two types of such devices are commonly used for position-sensing applications[1,2]. The segmented PSDs or four-quadrant detectors are used for high precision and low signal-level applications where range of movement is relatively smaller or the alignment is the objective. On the other hand, the continuous PSDs or the lateral-effect photodiodes are used for wider displacement measurement with high linearity, good resolution and fast response[3].

Applications of PSDs are even more diverse and widespread in the industry, including alignment, displacement sensing and as a part of other analysis instrumentation. In such environment, the system laser source is co-existing with different nearby light sources, coherent or otherwise, along with their reflections and back-scatters from various nearby surfaces. Some of the systems may involve scanning or rotating laser beams too, which may have enough energy to effect the PSD measurements in the form of periodic pulses.

Such random illumination noises may take the form of different sources types, e.g., directional, point or extended and may fall on the detector surface in different shapes or spatial distributions. They may produce unwanted outputs while mixing with the real signal, which is coming direct from the source or via the reflector onto the detector surface. These noise sources have been mentioned or described by some of the earlier authors[1,2,4]. Nonetheless it is felt that a detailed operational analysis is still required.

It may also be mentioned that for more critical measurement applications, modulation of light source is used synchronized with receiver, to avoid the effects of background light. But on the other hand, such systems become unfeasible in many standard applications due to the practical reasons such as needed compatibility with simpler light sources, reduced technical complexity and lower system cost. Thus whole lot of industrial position measurement systems are still produced and utilized with un-modulated continuous light sources[5,6], directly effected by other illuminations. Also important is the fact that, as given by Makynen *et al.*[1], even the modulated light reflected-beam sensors do suffer from stray illuminations problem in the form of unwanted reflections from close-by objects and outlined this problem along with an effort for a solution. Thus the position response analysis presented here does also apply to these sensor types while considering the effects of such stray reflections.

PSDs basing on lateral-effect have a continuous construction in terms of their light-sensing area, which characterizes them from the other segmented position-sensitive detectors. Thus their construction is in

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the form of a single continuous photodiode, as shown in Fig. 1. As the light falls on a specific portion of LEP, the generated current carriers are divided between the extended edge electrodes on each side. This division is in proportion to the encountered respective conductance, or in inverse proportion to the relative distances of the current paths between the illuminated region and the respective electrode[2].

The important features of these lateral-effect devices include position measurement of the incident light spot for the larger dynamic range or upto the edges of the devices. Additionally, the transfer characteristic for the light spot position measurement has very good linearity for the entire range[1]. This gives them an edge over the segmented photodetectors for many of the applications where continuous position measurement is needed. Another useful feature is that the position is measured for the centroid of the incident light beam. This makes them largely indifferent to the spot size and shape[7]. The position of the light spot is calculated from the terminal currents such that the output limits are normalized to −1 and +1 at the sensor edges. The final position along x-axis measured from the center of the detector is given by following for the general duo-lateral and tetra-lateral effect PSDs[8,9]. Similar formula will be used for the y-axis position calculation in dual-axis PSD.

$$P_x = \frac{L}{2}\left(\frac{i_2 - i_1}{i_2 + i_1}\right) \tag{1}$$

Noise beams and illuminations: The disturbing lights and illuminations may be coming from different types of sources and may be taking different spatial distribution and characteristics. Considering the sources of illuminations, the major sources have been described by Beraldin *et al.*[10] to be ambient illumination, direct sunlight and other laser sources. These sources have been described to be the limiting factors for the performance or fluctuation-free resolution obtained from the operation of the continuous or lateral-effect PSDs[10]. In the following we categorize them according to their characteristics and the spatial distribution of their light on the PSD surface and also analyze them one by one from the point of view of the normal operation of PSDs and the disturbances caused in its output.

Probably the most obvious source of external noise in an optical system is background radiation. Any detector will anyway be facing the black-body radiation from the background which happens to be at a specific temperature during the operation or measurement, even if specific sources are not present to emit the interfering or disturbing radiation. According to Plank's Law, this minimum background radiation illuminating any detector, or PSD to be specific, will be given as following[4], while other descriptions and equations are also used[11]. Unless their intensity is high, their usual effect may be smaller and similar to other diffused illuminations to be described hereafter.

$$\left\langle P_{opt} \right\rangle_{BG} = \int_{\Delta\nu} \frac{1}{4} I(\nu) d\nu A_{det} \frac{d\Omega}{4\pi} \tag{2}$$

Probably the major source of disturbance for our analysis can be that from other directional laser beams falling on the surface of a lateral-effect PSD simultaneously, as shown in Fig. 2. Similarly, other directional light beams and non-laser lights, which fall on the detector surface in a shape approximating a beam, may also be included in this category[12]. Similar effect will also be produced by the illuminations, which are not directional in nature but are converted to a spot by the receiver optics. The most obvious example may be that of parallel rays coming from a distant source and converted to a spot by the positive lens used in front of the PSD.

For the normal direct-beam or reflected-beam position sensor based on a Lateral-effect PSD, the output current produced on the PSD terminals by the main or actual incident beam is function of certain parameters as $i_j = i_j\ (I_s, x_s, y_s)$ for j = 1-4. Here I_s is the intensity of the actual beam incident on PSD's surface and x_s, y_s give the position of the centroid of the beam on PSD's surface. Similarly, if the noise beam is falling on the surface, the output current component due to this beam may be given as $i_j' = i_j'\ (I_n, x_n, y_n)$ for j = 1-4. Here, I_n is the intensity and x_n, y_n give the position of the centroid of the noise beam on the PSD's surface.

The next important type of interfering illumination to be considered is the one, which is not beam-like or otherwise is not narrow enough and falls on whole of the PSD's surface area. These include the point sources whose light is falling direct on the PSD or the extended sources, diffuse reflections and background illuminations, which do not form a limited spot even after passing through the receiver optics. Ambient light is the most obvious example of this category. Simplifying their effect on the PSD, they may be approximated by a wide spot covering whole of the PSD area and having the centroid in the middle or the center of PSD, as shown in Fig. 3. Thus as earlier, $i_j' = i_j'\ (I_{ill}, 0, 0)$ for j = 1-4. Here, I_{ill} is the intensity and 0, 0 indicate the middle position of the centroid of the interfering illumination on the PSD's surface.

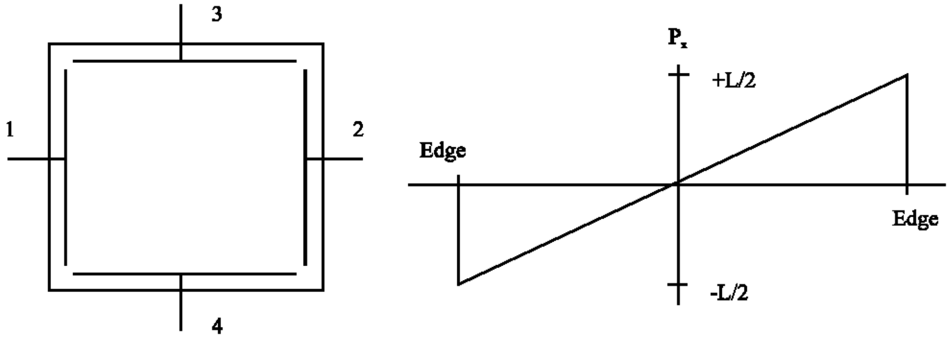

Fig. 1: Geometrical shape and transfer curve of Lateral effect PSD

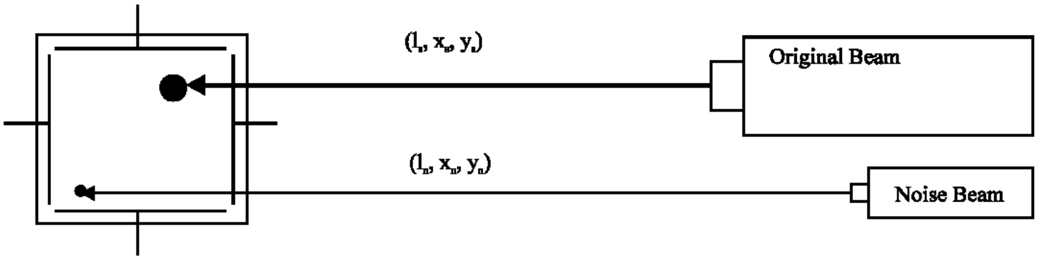

Fig. 2: Noise beam disturbing the original beam on PSD surface

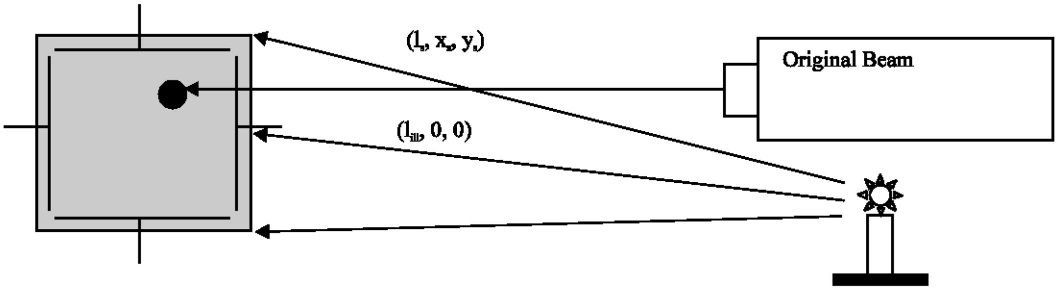

Fig. 3: Diffuse illuminations disturbing the original beam on PSD surface

A specific category may be that of the pulsating lights or the scanning laser beams falling on the surface of PSD in the form of a pulse train. Although they may also be falling on a specific area of the detector, much more common are going to be those approximating the diffuse illuminations covering almost entire area. This is to be expected as there is much more chance of backscatter interfering on the PSD surface instead of direct scanning light and they are expected to take the form of diffuse illumination. The output current in this case is function of one more parameter as $i_j' = i_j'$ (I_{ill}, 0, 0, DC) for j=1-4. Here DC represents the net duty cycle of the interfering pulses impinging on the surface of PSD.

Position response error with optical noise: For the normal single-beam operation, PSD gives the centroid position of the incident signal beam calculated by the individual currents as given before.

$$P_{Signal} = \frac{L}{2}\left(\frac{i_2 - i_1}{i_2 + i_1}\right) \tag{3}$$

Suppose that instead of the signal beam, there is a 'noise beam' falling on the surface of PSD and generating its own currents on the output terminals. The position of the noise beam can be calculated by the similar formula as following:

$$P_{Noise} = \frac{L}{2}\left(\frac{i_2' - i_1'}{i_2' + i_1'}\right) \quad (4)$$

So, for the single-beam operation, calculation of the beam position is carried out in the similar manner for both of the cases. But what will be the behaviour of the device when both the beams are incident on the surface of the PSD at the same time? According to Kawasaki and Goto[7], the output of PSD, calculated using the terminal currents, in this case should be equal to the intensity-weighted mean of both the light positions. Thus the final position and the error from the signal position may be given as following:

$$P_{Measured} = \frac{I_{Signal}}{I_{Signal} + I_{Noise}} P_{Signal} + \frac{I_{Noise}}{I_{Signal} + I_{Noise}} P_{Noise} \quad (5)$$

$$P_{Measured} = P_{Signal} + \frac{I_{Noise}}{I_{Signal} + I_{Noise}}\left(P_{Noise} - P_{Signal}\right) = P_{Signal} + \delta P \quad (6)$$

$$\delta P = K_{Intensity} dP = K_{Intensity}\left(P_{Noise} - P_{Signal}\right) \quad (7)$$

Thus the shift in measured position due to the presence of interfering beam depends on the mutual distance between both the sources and on the fraction of the noise intensity within the total intensity falling on PSD. This is the case when a second noise beam, which is directional in nature, is interfering with the original signal beam on the PSD. What may happen in the case where a broad illumination from a point source or an extended source is covering whole of the surface and is interfering with the original signal beam? As discussed earlier, its centeroid may be taken to be at the center of the PSD. Here the change in the final position brought by the illumination is as following.

$$\delta P = K_{Intensity} dP = K_{Intensity}\left(-P_{Signal}\right) \quad (8)$$

Last case is about the specific category of the pulsating lights or the scanning laser beams falling on the surface of PSD in the form of a pulse train, while illuminating the PSD area as a whole. In this case the intensity of the interfering noise is actually modified in terms of the duty cycle fraction, but as the intensity of the noise is taken to be much smaller, i.e., $I_n << I_s$; thus the whole of the intensity multiple may be modified to include the DC fraction.

$$\begin{aligned} \delta P &= K_{Intensity(Duty-Cycle)} dP = \frac{DC \times I_{Noise}}{I_{Signal} + DC \times I_{Noise}} \times dP \\ dP &\cong K_{Intensity} K_{Duty-cycle}\left(-P_{Signal}\right) \end{aligned} \quad (9)$$

EXPERIMENTAL METHOD

Experimental setup for evaluating the effects of noises on the position measurements included a lateral effect PSD-based position measurement system, which was illuminated by a prime laser beam along with a noise beam or noise light source. Two laser sources used were Suwtech diode-pumped green lasers emitting at 0532 nm, which is produced by doubling the frequency of Nd:YVO$_4$ crystal output. One laser was DPGL-2100 giving upto 100 mW output with modulation control and other was DPGL-3001F giving about 1 mW output. The beams of these lasers are CW, TEM$_{00}$ with beam diameter <1.0 mm and beam divergence <1.0 mrad.

The position-sensitive detector used was Melles Griot 9x9 mm dual-axis lateral-effect silicon detector. This has 8 mm calibrated diameter and position resolution of ±1 µm. The detector was used in conjunction with Melles Griot microcomputer-based spot on optical beam position and power measurement system, model 13PSL002-PCI. The system provides software control, software linearization, selective data logging and data acquisition rate of 20 Hz. One laser head was moved by placing on PI translational movement IntelliStage C531.5i, featuring computer-control, 306 mm range and 0.1 µm linear resolution. Whole apparatus was placed on Newport RP Reliance Sealed Hole Table Top, which was mounted on Newport isolation supports. The construction of the test apparatus is shown in the given Fig. 4.

It was noticed that certain factors hampered the stability and repeatability of the digitized data very much, so care was taken about them to avoid any error in the

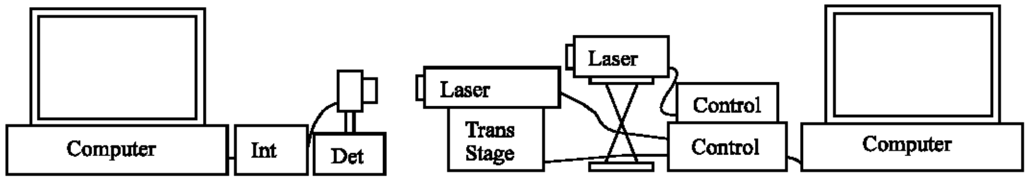

Fig. 4: Experimental setup with computers, lasers and position detection system

readings. Ambient temperature was maintained at 20-25°C as the drift in both directions was apparently effecting the data stability. The incident intensity on the detector was used close to 1-1.5 mW, as much lower intensities were giving more jittery readings and higher intensities were risking detector saturation. Control of ambient light was practiced in order to avoid any systematic error in the data and bare minimum was used. As per laser usage practice, some warm-up time was given for the lasers and equipment temperature to stabilize, as more shaky data was noticed otherwise.

RESULTS AND DISCUSSION

As per noise categories described in earlier sections, the first type of noise considered is that of the interfering directional beams which fall on the detector surface and form a limited light spot. To evaluate their effect, a signal beam was projected on the PSD surface approximately at its center. The interfering beam source was placed on the translational stage and was scanned across the PSD of net position were taken by casting it at different positions on PSD surface with the intervals of 1 mm. Two sets of data were collected with the noise beam intensity being approx 10% of the signal beam intensity in the first set and being approx 5% of the signal intensity in the second set. Both the sets of position data were compared with the calculated outcomes after the beam disturbance as per theory developed earlier. Data points were plotted with calculated position on one axis and the experimental position on other axis and were shown along with the straight line of ideal comparative values in Fig. 5 and 6.

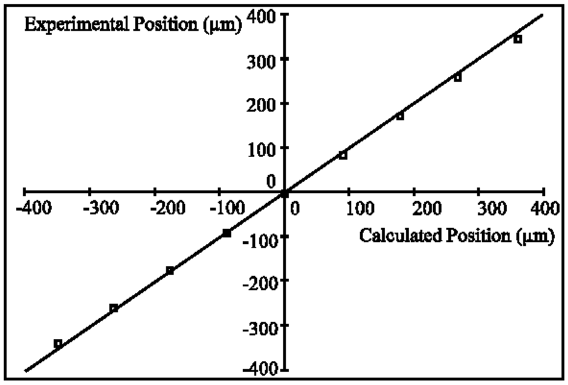

Fig. 5: Plot of position measurements in presence of 10% disturbance beam

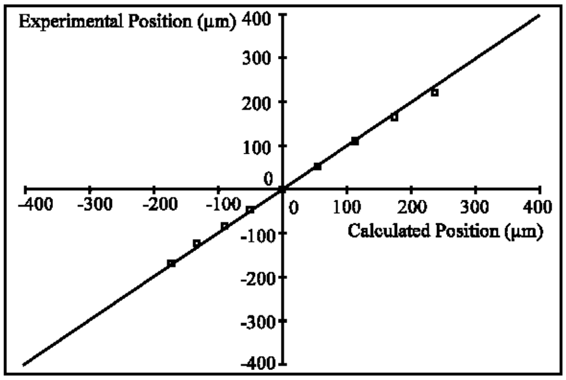

Fig. 6: Plot of position measurements in presence of 5% disturbance beam

As seen in the plotted curves, both the sets of calculated and experimental data coincide well with each other. The maximum difference in both of the data sets is about 20 μm while the maximum scale of reading is 8000 μm (−4000 to +4000 μm). This puts the maximum error encountered in both the experiments of 10 and 5% noise at about 0.25% of full-scale reading.

The second type of optical noise mentioned earlier is that caused by the stray illuminations, which are not forming a spot on the surface and they are rather covering the entire area of PSD. This type of disturbing illumination was produced for experimentation by simultaneous effect of multiple room lights, while their total intensity falling on PSD was almost symmetrical about the center of PSD, specifically in x-direction, which is the axis of interest at the moment. The signal beam was projected at the ends of the calibrated area of PSD, i.e. at – 4.0 and + 4.0 mm. The measurements were taken with the illumination intensity being about 5 and 10% of the signal intensity. The effect of illumination on the position measurement from PSD was noted and compared with the calculated outcome differently for both the intensity percentages in Fig. 7 (squares for 10%).

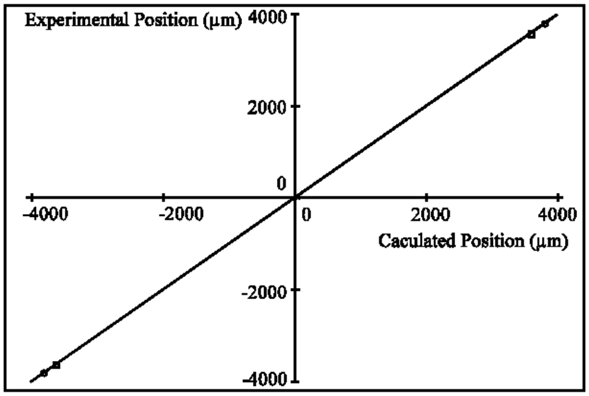

Fig. 7: Plot of position measurement in presence of disturbing illumination

As seen in the plot, the calculated and experimental data coincide well with each other. The maximum difference in these data points is about 30 μm in the maximum scale of 8000 μm. This puts the maximum error

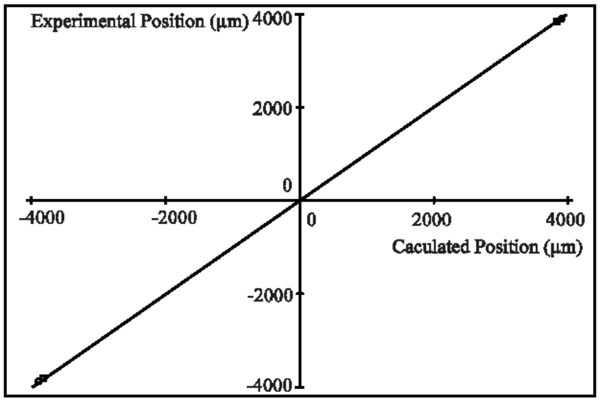

Fig. 8: Plot of position Measurment in presence of disturbing pulsed illuminatuion

encountered in this experiment at about 0.375% of full scale reading.

To simulate the pulsating or scanning lasers, the interfering beam was modulated at 1.0 kHz with 50% duty cycle. It was projected on the center of the PSD detection area to simulate the falling pulsating reflections or rotating lights. The signal beam was projected at the ends of the calibrated area of PSD. The measurements were taken with the unmodulated interfering intensity being about 5 and 10% of the signal intensity. The effect of interfering pulses on the position measurement from PSD was noted and compared with the calculated outcome differently for both the intensity percentages in Fig. 8 (squares for 10%).

As seen in the plot, the calculated and experimental data coincide well with each other. The maximum difference in these data points is 20 µm in the maximum scale of 8000 µm. This puts the maximum error encountered in this experiment at about 0.25% of full scale reading.

CONCLUSIONS

Theory and analysis of stray beams and optical noises disturbing the position response of lateral-effect position-sensitive devices were presented in this study. It is found that the error introduced in the position measurement in the presence of an interfering beam or δP, is proportional to the distance between the centroids of both the beams and to the fraction of the noise intensity in the total. In case of a uniform or broad illumination, the same analysis applies while the centroid of the interfering illumination should be taken at the center of the PSD area. In case of scanning or pulsating lights, the produced effect should be decreased in proportion with the beam duty cycle. These results have been verified experimentally and the obtained data is within a fraction of a percent of the predicted calculations.

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