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by

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Discussion of Several Problems in Four-quadrant Photoelectric Tracking Technology

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Abstract A four-quadrant detector is frequently used as a photoelectric sensor to detect the azimuth of a target in photoelectric tracking devices including the laser seeker, laser theodolite, etc. In the process of tracking, the optical signal coming from a target is focused and projected, through an optical system, onto the photosensitive surface of the four-quadrant detector to form a target image spot. It is through the distribution of the target image spot on the four quadrants that the four-quadrant detection system calculates the azimuth deviation angle of the target relative to the optical axis of the tracking system. An ideal detection system should produce deviation data which are in a linear relationship with the actual deviation of the target relative to the center of the four-quadrant detector. Nonetheless, the ideal conditions can hardly be realized owing to various constraints. To find proper means, a detailed calculation was made of some vigorous constraints, such as the data extraction method, image spot dimensions and the like. In spite of the foregoing efforts, some of the problems are still expected to be studied further. For instance the four-quadrant diagonal algorithm may produce entirely different signal transfer characteristics of the system because of different normalization methods employed, and the enlargement of the target imaging spot on the four-quadrant detector may impose an effect on the curve slope of the signal transfer function, etc. From this, however, a good deal of useful information has been gained.
Key Words: Photoelectric sensor, photoelectric tracking, data sampling

The four-quadrant detector is often used as a photoelectric sensor in photoelectric tracking devices like the laser seeker, laser theodolite, etc. Such a detector is designed to realize target tracking by detecting the azimuth of the tracked target and further controlling the action of the servomechanisms, including the helm. During the tracking process, the optical signal from the target is focused and projected, through the optical system, onto the photosensitive surface of the four-quadrant detector to form a target image spot. By using the distribution of the target image spot on the four quadrants, the four-quadrant detector system can calculate the target azimuth deviation relative to the optical axis of the tracking system, i.e. calculate its deviation angle through calculating the image spot location deviation relative to the four-quadrant center. An ideal detection system is one where the deviation data calculated are in a linear relationship with the actual target deviation relative to the four-quadrant center. But in fact, ideal conditions as such can hardly be arrived at due to various constraints. Although this problem has been much discussed, it is expected to be worked on further. With this in mind, a detailed calculation was made in our related research projects of the above-mentioned constraints to meet the required technical specifications by selecting proper means based on our actual conditions.

1. Deviation Data Calculative Methods

There are many methods to calculate deviation data by using the distribution of the target image spot on the four quadrants, among which the typical ones are the four-quadrant add-subtract method, and diagonal subtract method.

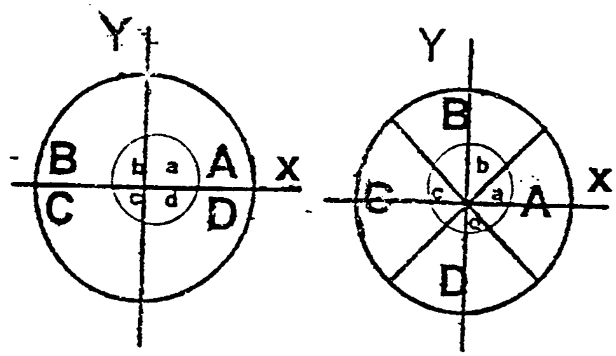

Fig. 1. A Schematic Diagram Showing Two Deviation Data Calculation Principles of the Four-quadrant Detection System

In the four-quadrant add-subtract method (see Fig. 1a):

$Ex=Sa+Sd-Sb-Sc$; $Ey=Sa+Sb-Sc-Sd$

In the diagonal subtract method (see Fig. 1b):

$Ex=Sa-Sc$; $Ey=Sb-Sd$

where Ex is the component of deviation data in x direction; Ey is the component of deviation data in y direction; Sa, Sb, Sc and Sd respectively are the area of the target image spot in the four quadrants A, B, C and D.

Note: Here, the light intensity of the target image spot is assumed to be in a uniform distribution.

To eliminate the effect of the image spot intensity, the above-mentioned data are generally to be normalized.

For a comparison, the two different calculation methods are introduced. To make the analysis result more concise, analysis was conducted only for the forward movement of the target image spot along the X axis of the rectangular coordinate. In addition , the target image spot intensity is assumed to be uniformly distributed. The image spot negative movement along X axis or movement along Y axis can easily be derived from the symmetric character of the data.

1.1 Four-quadrant Add-subtract Method (see Fig. 2)

Here, we suppose the radius of the photosensitive surface of the four-quadrant detector R=1; the radius of the target image spot r=0.5. When the image spot moves from the original point of the coordinate along the path shown in the figure, the area of the spot in quadrant **A** is:

$$Sa = \int_{0}^{a+0.5} \sqrt{r^2-(x-a)^2}\, dx$$

and its area in quadrant B is:

$$Sb = \int_{a-0.5}^{0} \sqrt{r^2-(x-a)^2}\, dx$$

where a is the image spot offset measured along the X axis. The corresponding Ex-a curve is shown in Fig. 3. Thus, the normalized deviation data are:

$$Ex = (Sa - Sb) / (Sa + Sb) \qquad (1) \tag{1}$$

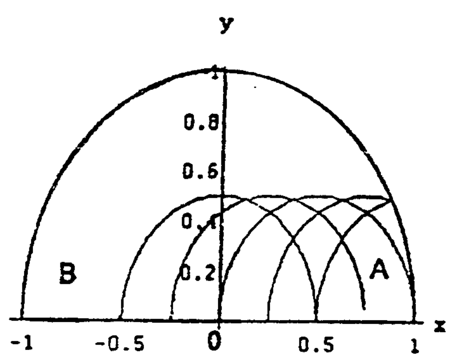

Fig. 2 Movement Path of Image Spot with a Radius r=R/1 along X Axis

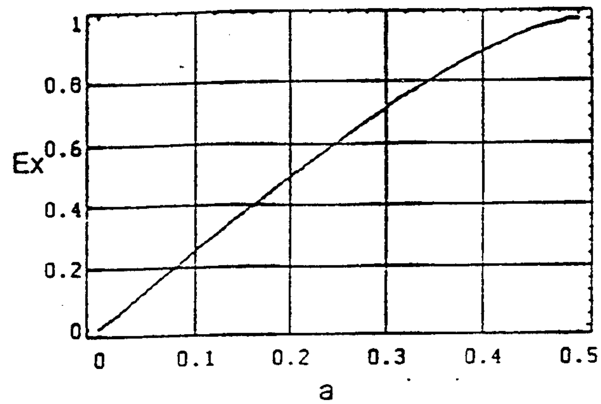

Fig. 3 Ex-a Normalized Dependence Curve Derived from Four- quadrant Add-subtract Method at r=R/2

It can be seen from Fig. 3 that when the image spot center is slightly offset relative to the four-quadrant center, the Ex offset measure a, of the system-calculated deviation data, is in an approximately linear relation. The approximately linear area is a=(0-0.3)R. When the image spot center deviates from the four-quadrant center as much as a=R/2, the spot is completely out of quadrant B, and the normalized deviation data reach a maximum value Ex=1 until the image spot disengages from the four-quadrant photosensitive area. In this case, a=R+r=1.5 and Ex drops dramatically to zero.

1.2 Diagonal Algorithm 1 (see Fig. 4)

The diagonal algorithm can serve in deriving two normalized curves due to different normalization methods. One variant of the algorithm is as follows:

$$Ex=(Sa-Sc)/(Sa+Sc) \qquad (2)$$

where Sa and Sc, respectively, are the area of the target image spot in quadrants A and C of the four-quadrant photosensitive surface as shown in the figure, which can be expressed as:

$$Sa = \int_0^{a1} x \, dx + \int_{a1}^{a-0.5} \sqrt{0.5^2 - (x-a)^2} \; dx \;\Big|\; 0 \le a \le 0.5$$

$$Sa = \int_0^{a1} x \, dx + \int_{a1}^{a3} \sqrt{0.5^2 - (x-a)^2} \; dx + \int_{a3}^{a-0.5} \sqrt{0.5^2 - x^2} \; dx \;\Big|\; (R+r) \ge a > 0.5$$

$$Sc = \int_{a-0.5}^{a2} \sqrt{0.25 - (x-a)^2} \; dx + \int_{a2}^{0} -x \, dx$$

where $a1 = (a + \sqrt{0.5 - a^2})/2; \qquad a2 = (a - \sqrt{0.5 - a^2})/2; \qquad a3 = (1 + a^2 - 0.25)/2a$

This method can derive an Ex-a dependence curve as shown in Fig. 5. It is known through a curve fit analysis that this curve is approximate to a sinusoidal curve. The curve still displays good linearity near the original points of the coordinates, but the linear area shrinks to a≈(0-0.2R).

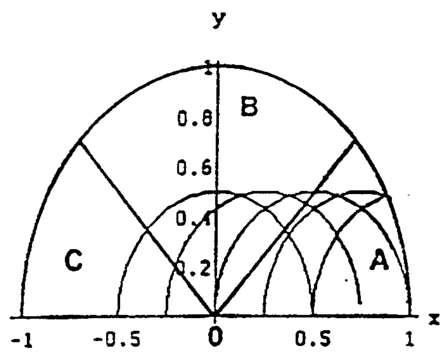

Fig. 4. Movement Path of Light Spot with r=R/2 along Four-quadrant Diagonal Line(X axis)

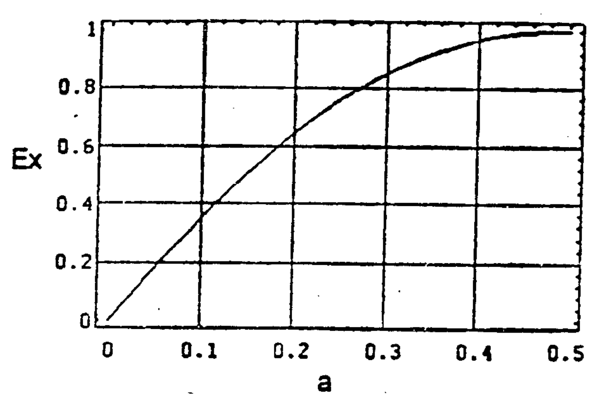

Fig. 5 Ex-a Normalized Curve Derived from D iagonal Algorithm 1 at r=R/2

1.3 Diagonal Algorithm 2

In the second normalization method:

$$Ex=(Sa-Sc)/(Sa+Sb+Sc) \tag{3}$$

where

$$(Sa + Sb + Sc) = \int_{a-0.5}^{a+0.5} \sqrt{0.25-(x-a)^2}\,dx$$

The definitions of Sa and Sc are the same as in the diagonal algorithm 1. The curve derived from this algorithm is shown in Fig. 6 indicating that this normalization algorithm possesses an excellent linear character with a linear area extending to over a≈0.5R.

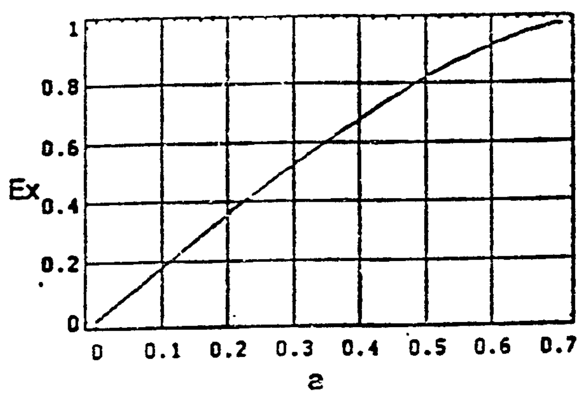

Fig. 6 Ex-a Normalized Curve Derived from Diagonal Algorithm 2 at r=R/2

2. Effect of Target Image Spot Dimensions

The above discussion is conducted on the condition that the radius of the image spot r=R/2. The following discussion is focused on the effect of the target image spot on the calculations. Again, we suppose the light intensity of the target image spot is uniformly distributed, and the image spot has the same dimensions as that of the photosensitive surface of the four-quadrant detector, i.e. the radius of the image spot r is equal to that of the four-quadrant photosensitive surface R. When the image spot center is coincident with the four-quadrant center, the light energy (power) on the image spot is totally projected on the photosensitive surface of the detector and is fully utilized. Yet once the image spot deviates from the four-quadrant center, then part of the light spot will fall beyond the detector and thereby gets lost, which, at the same time, will change the distribution of the image spot and affect the deviation data calculations.

When the target image spot is identical to the four-quadrant photosensitive surface in dimensions, the movement path of the spot relative to the four-quadrant center is as shown in Fig. 7. The corresponding calculation formula still remains: Ex=(Sa-Sb)/(Sa+Sb) but Sa and Sb change to:

$$Sa = \int_0^{a/2} \sqrt{1-(x-a)^2}\,dx + \int_{a/2}^{1} \sqrt{1-x^2}\,dx\,; \qquad Sb = \int_{a-1}^{0} \sqrt{1-(x-a)^2}\,dx$$

The calculations are shown in Fig. 8 suggesting that the curve slope becomes remarkably gentle due to the enlargement of the target image spot. Additionally, the curve becomes downward-concave because part of the image spot falls beyond the photosensitive surface.

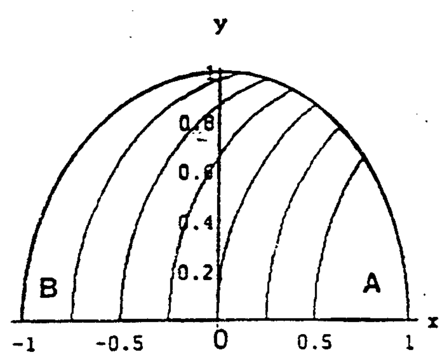

Fig. 7. Movement Path of Target Image Spot Along the X Axis

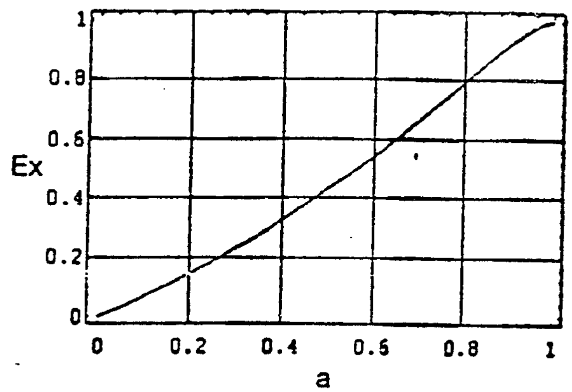

Fig. 8. Ex-a Normalized Curve Derived from Four-quadrant Add-subtract Method at r=R

Effect on the diagonal algorithm

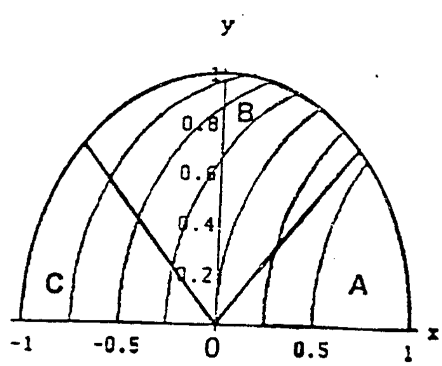

Fig. 9. Movement Path of Image Spot Along Four-quadrant Diagonal Line

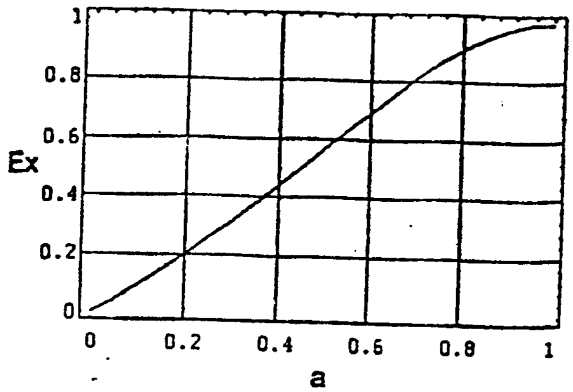

Fig. 10 Ex-a Normalized Curve Derived from Diagonal Algorithm 1 at r=R

Based on the first normalization method of the diagonal algorithm Ex=(Sa+Sc)/(Sa+Sc), a curve can be acquired as shown in Fig. 10. The definition of Sc in the Eq is the same as at r=R/2, but Sa changes to:

$$Sa = \int_0^{a4} x\,dx + \int_{a4}^{a+1} \sqrt{1-x^2}\,dx \quad \Big|\, 0 \le a \le 1$$

$$Sa = \int_{a-1}^{a5} \sqrt{1-(x-a)^2}\,dx + \int_{a5}^{a4} x\,dx + \int_{a4}^{a+1} \sqrt{1-x^2}\,dx \quad \Big|\, (r+R) \ge a > 1$$

where

$$a4 = (a + \sqrt{1-a^2})/2; \quad a5 = (a - \sqrt{1-a^2})/2$$

The second normalization method of the diagonal algorithm still employs the computing formula (Sa-Sc)/(Sa+Sb+Sc), where the definitions of Sa and Sc are the same as in the first normalization method; Sa+Sb+Sc can be expressed as:

$$(Sa + Sb + Sc) = \int_{a-1}^{a+1} \sqrt{1-(x-a)^2}\,dx$$

The calculations are shown in Fig. 11 indicating that the enlargement of the curve image spot causes the deviation data curve slope and slope variation to become gentle.

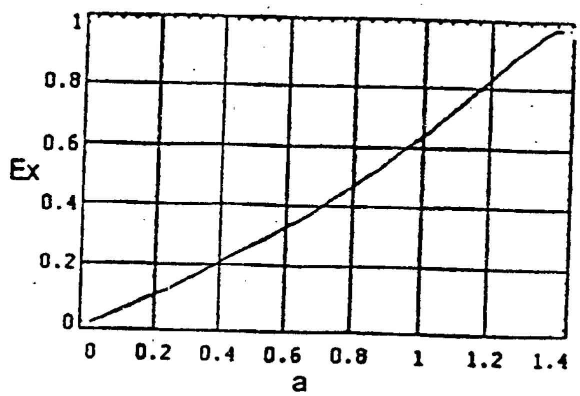

Fig. 11. Ex-a Curve Derived from the Second Normalization Method of Diagonal Algorithm at r=R

3. Conclusions

To make a comparison between the foregoing calculations, all the curves involved in the discussion are put together in Fig. 12. The schematically shown curves as well as the above discussion lead to the following conclusions:

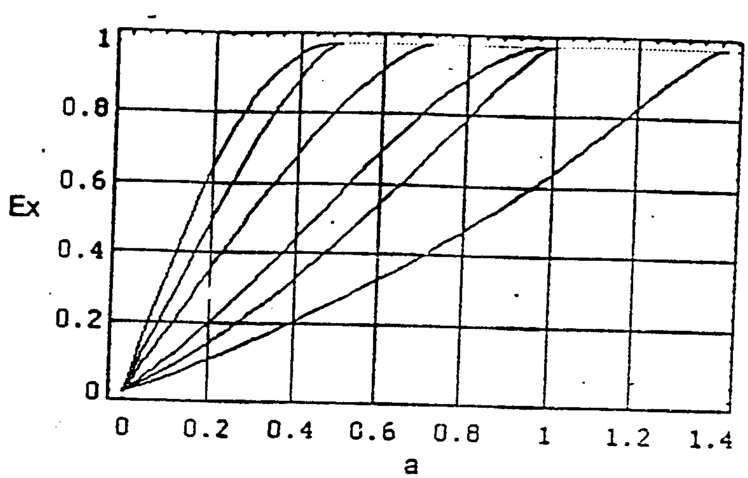

Fig. 12 Normalized Ex-a Curves under Various Conditions

(1) With the same system hardware, different methods may produce entirely different system performance indexes. For instance the conventional four-quadrant add-subtract method, with its advantages of generating moderate curve slopes, slope variation rates, linearity and linear area, being a simple calculation process as well as affording convenient matching of hardware and software, has wide applications in various automatic photoelectric tracking systems. Alternatively, the diagonal algorithm, simple in calculation process, can serve in performing calculations with hardware alone and can also derive different system characteristics by selecting a proper normalization method, taking either a larger initial slope or a wider linear area.

(2) Using the same signal processing method, the dimensions of the target image spot projected on the four-quadrant photosensitive surface has a fairly strong effect on the signal transfer function of the system. With enlargement of the target, the slope of the Ex-a curve becomes gentle and in terms of the characteristics of the tracking system, its response to the target motion slows down. In photoelectric tracking systems without automatic focusing capability, the decrease of the tracking range may lead to the enlargement of the target image spot projected on the four-quadrant photosensitive surface, severely affecting the tracking mobility. Nevertheless, tracking of the gentle and wide signal transfer characteristics with a larger image spot proves to be even more favorable for the stability of the tracking system and target acquisition.

(3) Apart from algorithm and image spot dimensions, there are many other factors that may affect the performance of the tracking system, such as the non-uniform distribution of the target image spot intensity, image spot distortion produced by

the abaxial optical system, etc. These are all necessary considerations during the future system design.