Radiation Response Matrix of Array Charge Couple Device

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Abstract　As a sensor to convert image from optical to electrical signal, charge coupled device (CCD) has been paid much attention to its image quality which is directly related to the radiation response characteristic parameters. Since array CCD is gaining more and more popularity, a concept of "radiation response matrix" and an evaluation method are put forward, and used to describe radiation response of each pixel of CCD. By analyzing of this matrix, and clearly defining physical concept of each element, parameters such as absolute radiation response, non-linearity, dark noise, signal-to-noise of each pixel and non-uniformity of CCD are in one-to-one correspondence with mathematical relation of the matrix. Response characteristic coefficient of each pixel is obtained using the model of radiation response matrix analysis by a test on area CCD DALSA-FTF6080M. One application of this matrix is demonstrated. Experimental results show that non-uniformity of this CCD is 3.1%, its response is linear, and its dark noise is 3.84. This method is feasible and practical, and it satisfies the requirement of the objective evaluation of array CCD.

Key words　array CCD; radiation response matrix; CCD photoelectrical performance; responsivity

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面阵电荷耦合器件的辐射性能函数

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摘要　电荷耦合器件(CCD)作为一个将光学图像转换到电子学图像的传感器,其成像质量与辐射响应参数的性能直接相关。针对面阵CCD越来越广泛的应用,提出利用"辐射响应矩阵"的概念和评价方法,表述面阵CCD每个像元的辐射性能参数。分析该矩阵,明确矩阵各元素的物理意义,并将面阵CCD每个像元的绝对辐射响应度、响应非线性度、暗噪声、信噪比以及非均匀性的数学关系与其物理含义一一对应。对面阵CCD DALSA-FTF6080M进行辐射性能检测,并利用辐射响应矩阵计算出各像元的响应系数。以测试结果为例,讨论和描述该矩阵的应用结果。实验结果表明:使用辐射响应矩阵可以计算出面阵CCD非均匀性为3.1%,该CCD近似成线性响应,暗噪声为3.84。此方法实用,满足对面阵CCD的客观评价。

关键词　面阵CCD;辐射相应矩阵;CCD光电性能;响应度

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1　Introdution

In the field of remote sensing, charge coupled device (CCD) devices show great potential to image information as an important photoelectric sensor. As its imaging permeability and sharpness fully recognized, CCD imaging has been an important application components in the field of imaging [1-2]. With the wide application of array CCD, manufacturers and departments in the field of remote sensing have began to pay more attentions to the radiation performance of array CCD devices. People have faced a problem how to select and use the array CCD. Radiation performance of array CCD determines the performance of remote sensing system in a great extent [3-4]. Radiation performance evaluation of CCD imaging system is a very important task which is one of the main basis for judging the completion

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situation of imaging.

Radiation response performance parameters of CCD devices mainly include radiation responsivity, non-uniformity, non-linearity, dark noise [3]. The 3D noise has been used to evaluate the performance of large array CCD device in recent years. Currently the detection technology of these parameters is being already matured, but it could be improved for the representation of array CCD method. Especially for large array CCD, it will be necessary to express all the performance properties of CCD by using a function formula with a clear physical significance. This paper presents a new method of expressing radiation performance parameters for each pixel of array CCD by matrix. With array CCD DALSA-FTF6080M as an example, it tests various parameters and evaluates different performances.

2 Radiation response matrix

The relationship is described by Taylor series between each pixel of digital output D and irradiance E which is received on photosensitive surface in CCD image [5-7]:

$$D = D_0 + R_1 \cdot E + R_2 \cdot E^2 + R_3 \cdot E^3 + \cdots + R_n \cdot E^n, \tag{1}$$

where, the physical meaning of D_0 is signal output of CCD at zero irradiation (dark signal output); R_1 is a linear response of CCD, also known as absolute radiation responsivity; $R_2, R_3, R_4, \cdots, R_n$ (coefficient of high-order as a subscript) are secondary high order response coefficients.

In Equ.(1), if the higher order coefficients are more close to 0, the CCD response is closer to the linear. In this case CCD response relationship is linear response, then this quantitative relationship can be simply expressed as [8-9]:

$$D = D_0 + R_1 \cdot E. \tag{2}$$

For $m \times n$ pixel array CCD, D of each pixel can be considered as an element of the matrix. Therefore, D of CCD can be formulated as a $m \times n$ matrix. Similarly, $m \times n$ pixel matrix can express the dark signal, linear response coefficient and higher coefficient of array CCD. As each pixel of array CCD meets the Equ.(1), you can use the "radiation response matrix" to present radiation response performance parameters of each pixel in array CCD.

$$\begin{bmatrix} D_{1,1} & & D_{1,n} \\ \vdots & D_{i,j} & \vdots \\ D_{1,m} & & D_{m,n} \end{bmatrix} = \begin{bmatrix} D_{0_{1,1}} & & D_{0_{1,n}} \\ \vdots & D_{0_{i,j}} & \vdots \\ D_{0_{1,m}} & & D_{0_{m,n}} \end{bmatrix} + \begin{bmatrix} R_{1_{1,1}} & & R_{1_{1,n}} \\ \vdots & R_{1_{i,j}} & \vdots \\ R_{1_{1,m}} & & R_{1_{m,n}} \end{bmatrix} \cdot E + \begin{bmatrix} R_{2_{1,1}} & & R_{2_{1,n}} \\ \vdots & R_{2_{i,j}} & \vdots \\ R_{2_{1,m}} & & R_{2_{m,n}} \end{bmatrix} \cdot E^2 + \cdots, \tag{3}$$

the matrix is the radiation response matrix of all pixels which is described by Equ.(1). The composition of the matrix has the following meanings.

2.1 Array CCD output digital value matrix

$\begin{bmatrix} D_{1,1} & & D_{1,n} \\ \vdots & D_{i,j} & \vdots \\ D_{1,m} & & D_{m,n} \end{bmatrix}$ is called as CCD array output digital value matrix, where $D_{i,j}$ is pixel digital output value of the i-row and j-column in array CCD.

According to the matrix, you can calculate the average value of CCD digital outputs

$$\bar{D} = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} D_{i,j}}{m \times n}. \tag{4}$$

Signal-to-noise ratio (SNR) is the ratio between the signal output with the root-mean-square (RMS) noise in array CCD. SNR is an important index of CCD imaging quality. D of the CCD output value being L times in a stable lighting condition, establishing a matrix of digital output value, the mean and noise of L times can be obtained for each pixel. SNR can be calculated with these data.

The SNR of the i-row and j-column pixel in array CCD is calculated as follows

$$R_{SNi,j}=\frac{\bar{D}_{i,j}}{\sqrt{\frac{\sum_{k=1}^{L}(D_{i,j,k}-\bar{D}_{i,j})^2}{L-1}}},\tag{5}$$

where $D_{i,j,k}$ is pixel digital output value of the i-row and j-column and k-image in array CCD. $\bar{D}_{i,j}$ is the ratio between $\sum_{k=1}^{L}D_{i,j,k}$ and L, as the average value of the i-row and j-column and L-image.

2.2 Dark signal matrix

Dark signal is the common characteristic of the most photovoltaic device of the majority, as one of the causes in image noise generation. Dark signal is CCD output digital value under no illumination. when the irradiance E=0, function matrix is as follow: $\begin{bmatrix} D_{1,1} & & D_{1,n} \\ \vdots & D_{i,j} & \vdots \\ D_{1,m} & & D_{m,n} \end{bmatrix}=\begin{bmatrix} D_{0_{1,1}} & & D_{0_{1,n}} \\ \vdots & D_{0_{i,j}} & \vdots \\ D_{0_{1,m}} & & D_{0_{m,n}} \end{bmatrix}\begin{bmatrix} D_{0_{1,1}} & & D_{0_{1,n}} \\ \vdots & D_{0_{i,j}} & \vdots \\ D_{0_{1,m}} & & D_{0_{m,n}} \end{bmatrix}$, which is called as dark signal matrix in array CCD, where $D_{0_{i,j}}$ is the background output value of the i-row and j-column in array CCD.

The value of CCD dark signal mean can be calculated by the dark signal matrix

$$\bar{D}_{dark}=\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}D_{0i,j}}{m\times n}.\tag{6}$$

If you create L dark signal matrix, you can calculate the CCD dark noise

$$D_{dark,noise}=\sqrt{\frac{\sum_{k=1}^{L}(D_{0_{i,j,k}}-\bar{D}_{i,j\text{dark}})^2}{L-1}},\tag{7}$$

where $D_{0_{i,j,k}}$ is the output dark signal of the i- row and j- column and k- image in array CCD, $\bar{D}_{i,j\text{dark}}=\frac{\sum_{k=1}^{L}D_{0_{i,j,k}}}{L}$ is the average dark signal of the i-row and j-column and k-image in array CCD.

2.3 Linear response coefficient matrix

$\begin{bmatrix} R_{1_{1,1}} & & R_{1_{1,n}} \\ \vdots & R_{1_{i,j}} & \vdots \\ R_{1_{1,m}} & & R_{1_{m,n}} \end{bmatrix}$ is called as linear response coefficient matrix, where $R_{1_{i,j}}$ is the linear response coefficient of the i-row and j-column pixel in array CCD.

Under the same illumination, the output difference of each pixel represents the inconsistency between responsivity of the pixels. This parameter is the characterization of the response non-uniformity (PRNU). The PRNU mainly describes the output characteristic of the relationship between each pixel. As for the cause of inhomogeneity, except for the inhomogeneity of the materials and moreover technology, the transfer efficiency of the device is also inhomogeneous, inhomogeneity of the amplifier performance is also an important cause of inhomogeneity. Based on linear response coefficient matrix, the response non-uniformity of array CCD can be calculated as the mean value of linear response divided by the standard deviation of each pixel linear response

$$P=\frac{\sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}(R_{1_{i,j}}-\bar{R}_1)^2}{m\times n-1}}}{\bar{R}_1}.\tag{8}$$

2.4 Nonlinear response matrix

High- order coefficient is called as $\begin{bmatrix} R_{2_{1,1}} & & R_{2_{1,n}} \\ \vdots & R_{2_{i,j}} & \vdots \\ R_{2_{1,m}} & & R_{2_{m,n}} \end{bmatrix} \begin{bmatrix} R_{3_{1,1}} & & R_{3_{1,n}} \\ \vdots & R_{3_{i,j}} & \vdots \\ R_{3_{1,m}} & & R_{3_{m,n}} \end{bmatrix}$ nonlinear coefficient matrix, where $R_{2_{i,j}}$, $R_{3_{i,j}}$ ⋯is the high-order coefficient of the i-row and j-column pixel in array CCD.

By way of polynomial regression analysis, the coefficient of each response can be calculated. If second-order coefficient is so small that its impact can be ignored, the response of array CCD can be called as linear. Nonlinear characteristics can be obtained by optimizing the linear regression coefficient of array CCD.

3 Test cases

In experiments, the image sensor DALSA- FTF6080M of interline transfer (DALSA company) with the total pixel number to be 6048×8082 and the pixel number of effective sensitization area to be 6000×8004 is used. Its dimensions and internal structure is shown in Fig.1 and Fig.2, respectively.

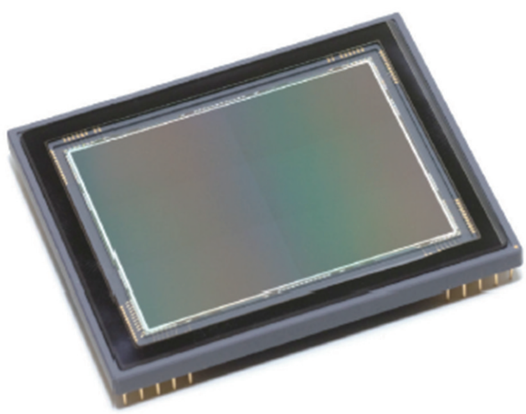

Fig.1 Formal size of area CCD DALSA-FTF6080M

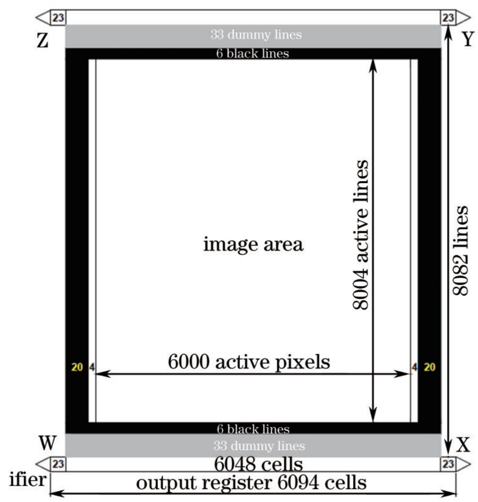

Fig.2 Inner structure of area CCD

For radiation response performance testing of CCD array, the main function is to calculate the relationship between the incident irradiance and the CCD digital output. Therefore one can use the regression analysis of mathematical statistics theory to deal with the functional relationship between the two quantities. By testing multiple CCD digital output, and E which is known in advance, it can determine the coefficients, R_1, R_2 and so on, by the method of regression analysis.

Laboratory equipment is mainly composed of calibration source and HR - 1500 spectroradiometer. Calibration source takes tungsten bromine lamp using the method of direct illumination CCD, according to the inverse square law, it shows that this approach can produce uniform illumination spot on the CCD, the non-uniformity in following 0.5% or less. By changing the distance between the CCD and the tungsten bromine lamp, and changing the irradiance on the CCD, CCD output is collected under each irradiance [10].

Since the array CCD DALSA-FTF6080M pixels being too much, as an example, here are 7 groups of incident irradiance and 4 pixels (2000, 2000), (2000, 2001), (2001, 2000), (2001, 2001) corresponding to output digital value, the response factor are caluated, as shown in Table 1.

Since each pixel meets the equation (1), you can use the method of polynomial regression analysis, the results are shown in Table 2.

Digital output value, the dark signal D_0, linear response coefficient R_1, and higher response coefficient R_2, R_3 of each pixel are expressed with "Radiation response matrix", as follows.

Table1 Illumination and DN of example pixels

Irradiance	Pixel No			
	(2000,2000)	(2000,2001)	(2001,2000)	(2001,2001)
0.138	993	987	989	989
0.107	770	766	767	744
0.070	535	531	536	529
0.043	357	362	361	360
0.026	238	237	230	228
0.014	149	148	150	151
0.007	86	85	84	83

Table 2 Response coefficients of example pixels

Parameters	Pixel No			
	(2000,2000)	(2000,2001)	(2001,2000)	(2001,2001)
D_0	56	57	55	55
R_1	6752.87	6707.64	6739.46	6663.38
R_2	2.3	1.6	1.3	2.1
R_3	0.18	0.15	0.26	0.11

$$\begin{bmatrix} & \vdots & \\ \cdots D_{2000,2000} & D_{2000,2001} \cdots \\ \cdots D_{2001,2000} & D_{2001,2001} \cdots \\ & \vdots & \end{bmatrix} = \begin{bmatrix} & \vdots & \\ \cdots 56 & 57 \cdots \\ \cdots 55 & 55 \cdots \\ & \vdots & \end{bmatrix} + \begin{bmatrix} & \vdots & \\ \cdots 6752.87 & 6707.64 \cdots \\ \cdots 6739.46 & 6663.38 \cdots \\ & \vdots & \end{bmatrix} \cdot E + \begin{bmatrix} & \vdots & \\ \cdots 2.3 & 1.6 \cdots \\ \cdots 1.3 & 2.1 \cdots \\ & \vdots & \end{bmatrix} \cdot E^2 + \cdots. \tag{9}$$

The various parameters can be calculated by the Matrix, as follows

a) Absolute radiometric response coefficient of each pixel: each element of the linear response coefficient matrix is displayed in the coordinate system shown in Fig.3;

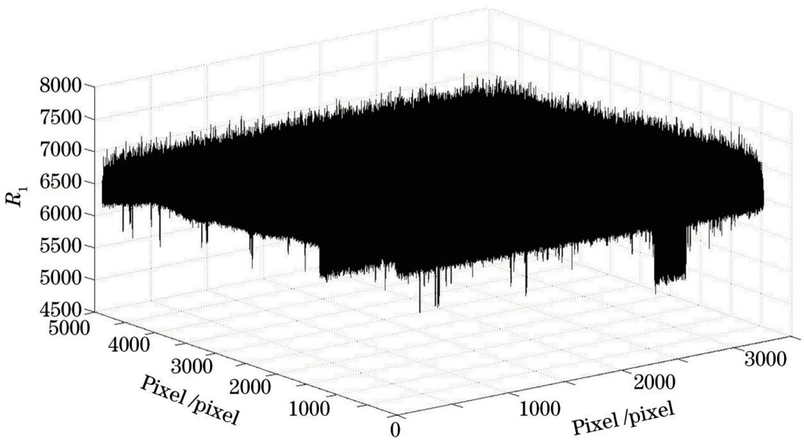

Fig.3 Absolute radiometric responsibility of area CCD

b) Dark signal mean: $\bar{D}_{\text{dark}} = 47.4$;

Dark noise: $D_{\text{Dark,noise}} = 3.84$;

c) Response non-uniformity: $P = 0.031$.

To take 2000- row and 3000- column CCD pixel as are example, the matrix shows the radiation response relationship of this pixel as follows

$$D = 50.80 + 6696.59E + 1.3E^2, \tag{10}$$

where the constant term D_0=50.80, and one order coefficient that is absolutely radiant responsivity R_1= 6696.59. Quadratic term coefficient is so small that it is ignored, therefore the CCD response is approximately linear. Linear fitting coefficient of association is 0.999.

4 Conclusion

Testing absolute radiation response of the array CCD, the "radiation response matrix" is built, which stores up the absolute radiation response of all CCD pixels and the higher term response. By

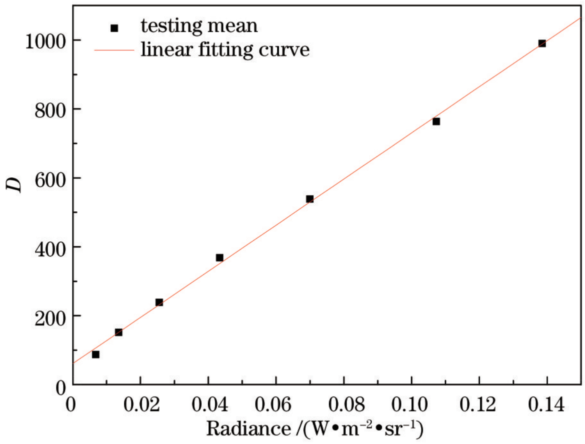

Fig.4 Response of CCD

analyzing the higher term coefficient to get the nonlinear relationship of response, comparing the difference of absolute radiation responsivity of each pixel, it can obtain the non- uniformity of responsivity and other radiation parameters. The test results are as follows:

1) Array CCD DALSA-FTF6080M response curve is approximately linear, and uniformity is better;

2) In the actual measurement, the average dark signal for the area CCD is 55. But by the establishment of CCD radiation response matrix, the value of dark signal is 47.4.For the indication, when the output value is very small, the accuracy is not enough according to Equ.(1). This problem needs to be solved.

By establishing a database with the matrix, and storing the radiation performance parameters of different modes, as input pixel number, you can compare each radiation parameter of array CCD directly to prick off the higher-performance CCD devices.

References

1 Han X ZH, Jiao SH J. Space Optics Remote Sensing Radiance [M]. Harbin: HRBIN Institute of Technology Press, 1994.

2 Hu J, Wang D. Detection and generation of multi-spectral TDICCD signals for space optical remote sensors [J]. Opt Precision Eng, 2009, 8(11): 1810-1818.

3 Ye P J, Liu F A, Cao H Y. The main performances and test method of the linear charge coupled device[J]. Chinese Space Science and Technology, 1997, 6(3): 44-51.

4 Luan Z J, Study a test system of linear CCD photoelectronic parameters [J]. Opt. Precision Eng., 1994, 2(4): 140-149.

5 Ren J W, Wan Z, Li X S, *et al*.. Radiation transfer characteristic and calibrating method for space optical remote sensor [J]. Opt Precision Eng, 2007, 15(8): 1186-1190.

6 Chen F, Zheng X B. Influence of spectrum not-matching on calibration precision of remote sensor[J]. Opt Precision Eng, 2008, 16(3): 415-419.

7 Ren J W, Liu Z X, Wan ZH, *et al*.. Radiometric calibration of off-axis three-mirror-anastigmat space camera with wide viewing field [J]. Opt Precision Eng, 2010, 18(7): 1491-1497.

8 Cui D J. Radiometric Calibration of Optical Remote Sensor [M]. Changchun: Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, 2002. 148-154.

9 Zhang L G, Li Y D, Liu Z X, *et al*.. Influence of total dose effects on TDI-CCD and corresponding test methods [J]. Opt Precision Eng, 2009, 17(12): 2924-2930.

10 Che N Z, Yan Y D. Radiance and Luminosity [M]. Beijing: Beijing Institute of Technology Press, 1990.