Research on Modeling and Simulation of Full Link Noise in CCD Camera System

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ABSTRACT

Through in-depth research on various noise sources and characteristics of the full link of the CCD camera system, a mathematical model of the CCD camera system noise was established, and the mathematical model of the noise was simulated and analyzed using MATLAB digital simulation software. At the same time, indoor noise testing of the CCD camera was conducted, and the simulation results were basically consistent with the measured results, verifying the correctness of the noise mathematical model. These research conclusions lay a reliable theoretical foundation for the subsequent search for accurate CCD noise suppression methods.

Key words: charge coupled device(CCD) , CCD camera, mathematical model, noise, simulation

1. INTRODUCTION

Charge coupled device (CCD) is a photoelectric conversion type image sensor, which was invented by W. S. Boyle and G. E. Smith of Bell Laboratory in 1969. CCD devices are characterized by self scanning, high resolution, easy connection to computers, low output noise, large dynamic range, high quantum efficiency, high charge transfer efficiency, wide spectral response range, and good geometric stability. Therefore, they are widely used in fields such as visible light imaging, space optics, and low light level night vision. Especially with the development of aerospace, CCD technology has great development space[1].

CCD cameras are mainly composed of optical lenses, CCD detectors, and related processing circuits. CCD image sensor is a semiconductor surface device that stores and transmits information in the form of charge packets. It can transform an optical image distributed in a spatial domain into a discrete signal voltage distributed in a temporal domain. The working process of CCD related circuits is mainly divided into charge storage, charge output, charge output, and image restoration. During charge transportation and storage of CCD, due to the isolation between the MOS tube and the outside, the noise of CCD itself is relatively low. However, during the generation, storage, and transfer of photogenerated charges, it is inevitable to generate some noise and interference. In order to obtain high-quality image signals, it is necessary to perform correlation processing on the CCD output signal, eliminate noise and interference as much as possible without losing image details, and improve the signal-to-noise ratio. Therefore, this article conducts in-depth research on the sources, types, and characteristics of CCD related noise, establishes a mathematical model of noise, establishes a CCD camera system noise analysis platform through mathematical simulation software MATLAB, simulates and analyzes the impact of CCD noise. Compares the results with laboratory imaging test images, the accuracy of the CCD camera system noise mathematical model is verified, providing data support for the mechanism analysis of subsequent noise suppression methods[2-3].

2. CCD NOISE SOURCE

The noise of CCD camera systems can be summarized as follows: photon shot noise, reset noise, dark current noise, mode noise, 1/f noise, broadband white noise, and quantization noise; The mode noise is divided into fixed mode noise and pixel response non-uniformity noise.1/f noise and broadband white noise are both noise introduced by amplification circuits. Therefore, they can be divided into on-chip amplifier noise and off-chip amplifier noise based on whether the amplification circuit is inside the CCD. Photon shot noise, reset noise, dark current noise, mode noise, and on-chip amplifier noise are introduced by the CCD detector itself. The off chip amplifier noise and quantization noise are introduced in the CCD video processing link. The CCD camera system noise model and each noise introduction diagram are shown in Fig.1[4-6].

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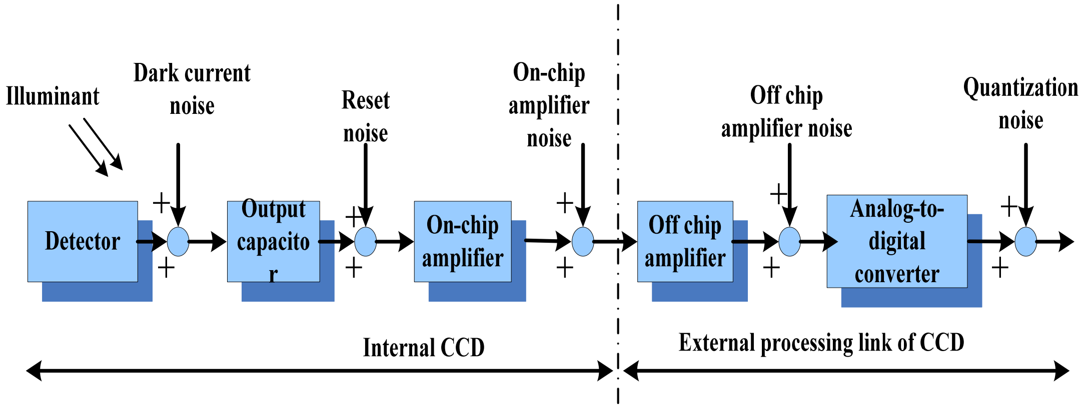

Figure 1. Diagram of The CCD camera system noise model

3. ESTABLISHMENT OF A MATHEMATICAL MODEL FOR THE FULL LINK NOISE OF A CCD CAMERA SYSTEM

3.1 Dark current noise

When the voltage on the MOS structure gate of the CCD exceeds the threshold voltage, the semiconductor surface below the gate is in a deep depletion state, resulting in potential traps. When there is no external charge injection, the potential well will gradually be filled due to the heat generation of the carriers, and the excitation process is a random process of Poisson distribution. Because this thermally generated carrier still exists in total darkness, the current generated is called dark current.

According to the statistical characteristics of Poisson distribution, if the number of electrons generated by the dark current signal is S_d, the magnitude of the dark current noise N_d is the square root of S_d in Eq.1. Therefore, to reduce the dark current noise, it is necessary to reduce the dark current signal.

$$N_d = \sqrt{S_d} \tag{1}$$

Dark current is closely related to temperature. When the temperature increases or decreases, the size of dark current will increase or decrease exponentially. When the temperature changes from 7°C to 10°C, the size of dark current will change by about twice. Therefore, cooling the CCD device is now the most effective way to suppress dark current noise. When the temperature drops to - 30°C, the dark current is so small that it can be ignored. Another reason for dark current noise is the presence of local lattice defects or impurities in CCD silicon. The specific magnitude of this dark current noise is closely related to the quality of the substrate material and the process.

3.2 Reset noise

Reset noise is mainly caused by the resistance RON thermal noise of the CCD output stage reset tube. After the CCD electrical signal is generated, the MOSFET transistor is turned on through a reset pulse. When the MOSFET transistor drain voltage is turned on, the capacitor C is charged. Therefore, the generated reset noise is calculated as follows.

The mean square value of the resistance thermal noise voltage is shown in Eq.2, where k is the Boltzmann constant, with a value of 1.38×10^{-23}J/K, T is the absolute temperature(K), and Δf is the noise equivalent bandwidth (that is, the frequency range of the ideal power gain response, in Hz, when the area of the ideal power gain response is the same as the area of the original circuit's power gain response).

$$V_n{}^2 = 4kTR\Delta f \tag{2}$$

For the RC circuit shown in Fig.2, the noise equivalent bandwidth is $1/4RC_S$, which can be substituted into Eq.3 to obtain:

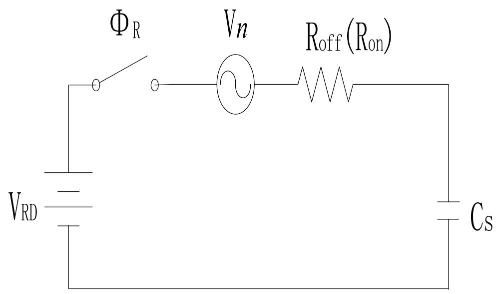

Figure 2. Equivalent RC circuit

$$V_n = \sqrt{4kTR\Delta f} = \sqrt{4kTR \times \frac{1}{4RC_S}} = \sqrt{\frac{kT}{C_S}} \tag{3}$$

If expressed in terms of electron number, it is shown in Equ.4, where q is the electric quantity carried by one electron, 1.602×10^{-19} coulombs.

$$N_{reset} = \frac{\sqrt{\frac{kT}{C_S}} \times C_S}{q} = \frac{\sqrt{kTC_S}}{q}(e^-) \tag{4}$$

3.3 On chip amplifier noise

The output structure of CCD includes not only a reset circuit composed of reset tubes, but also an output amplification circuit composed of output MOSFET tubes and load resistors. This output amplifier circuit introduces low frequency 1/f noise and white noise. White noise is mainly caused by thermal noise from the channel resistance and load resistance of the output tube. The generation of low-frequency 1/f noise is related to the additional electronic energy states at the boundaries of silicon and silicon dioxide. The magnitude of this noise is inversely proportional to frequency, so it is called 1/f noise. By comprehensively considering the two main noise sources, 1/f noise and white noise, the noise equation of the on-chip output amplifier can be obtained as shown in Equ.5.

$$V_{on-chip} = V_{nw}(1 + \frac{f_{knee}}{f})\sqrt{\Delta f} \tag{5}$$

Where V_{nw} is the white noise level. f_{knee} is the corner frequency (when the 1/f noise power is equal to the white noise power). Δf is the noise equivalent bandwidth of the output amplifier circuit, which is proportional to the pixel readout frequency. $N_{on-chip}$ is expressed in equivalent electron numbers in Equ.6:

$$N_{on-chip} = \frac{C_S}{Gq} V_{nw}(1 + \frac{f_{knee}}{f})\sqrt{\Delta f} \tag{6}$$

Where Gq / C_S is the output response sensitivity of the CCD, The unit is uV/e^-.

3.4 Off chip amplifier noise

The off-chip amplifier noise mainly targets the noise of the CCD external processing link. The main function of the video processing link is to transform the analog video signal output by the detector into a digital signal that can be processed by a computer. The purpose of video processing is to eliminate all kinds of noise and interference as much as possible without losing image details; And ensure that the image signal changes linearly with the target brightness within the dynamic range of the CCD.

Generally speaking, the noise of video processing links mainly considers two aspects:

(1) CCD noise.

This noise can be directly consulted in the device manual.

(2) Noise of the front amplifier.

In practical applications, when an operational amplifier is used to construct an amplifier with a certain gain for in-phase or inverse amplification, the amplifier amplifies the signal while also amplifying the input noise, so the amplifier has noise gain. For in-phase amplifiers, the signal gain is equal to $G_S = 1 + (R_f / R_g)$. It means that for in-phase amplifiers, the signal gain and noise gain are the same value. In addition, the internal resistance R_s and current noise I_n of the signal source also generate voltage noise. The following figure shows the noise model of the operational amplifier (considering resistance thermal noise and operational amplifier gain).

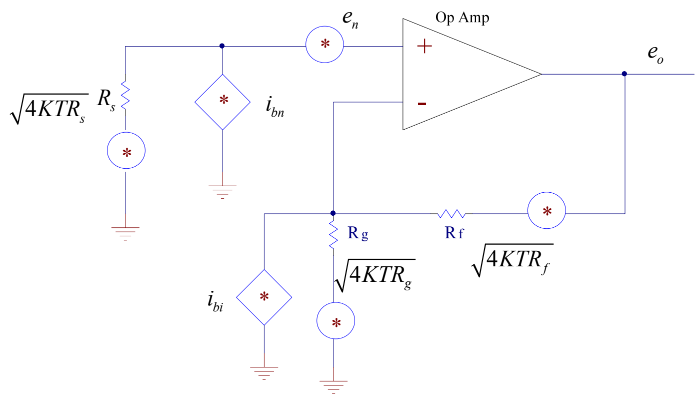

Figure 3. Noise model of operational amplifier

The figure above shows the input voltage noise e_n is in units of $nV/\sqrt{Hz}$. i_{bn} is the in-phase input current noise in units of $\rho A/\sqrt{Hz}$. i_{bi} is the inverting input current noise in units of $\rho A/\sqrt{Hz}$. For voltage feedback type operational amplifiers, i_{bi} is approximately equal to i_{bn} . For current feedback type operational amplifiers, i_{bi} is greater than i_{bn} .

As shown in Fig.3, the equivalent noise at the output end is shown in the following formula:

$$e_o = \sqrt{(4KTR_S + (i_{bn}R_S)^2 + e_n{}^2)(1+\frac{R_f}{R_g})^2 + (i_{bi}R_f)^2 + 4KTR_f(1+\frac{R_f}{R_g})} \tag{7}$$

3.5 Quantization noise

During the process of converting the analog video signal outputted by CCD into digital values through a high-speed AD conversion chip, quantization noise is inevitably introduced. The quantization error is actually a distribution function that obeys a uniform distribution, with an amplitude range of ± 0.5LSB.

From this, it can be obtained that the root mean square quantization error (or standard deviation of quantization error) is:

$$N_q = \frac{Q_{fw}}{2^n \times \sqrt{12}} \tag{8}$$

Q_{fw} represents CCD full well charge capacity. N represents Quantized digits of ADC. From Equ.8, it can be seen that the equivalent electron number of quantization noise is related to the quantization digit of the ADC and the full well charge capacity of the CCD.

4. MATLAB SIMULATION OF CCD CAMERA NOISE AND SIMULATION ANALYSIS OF LABORATORY MEASUREMENTS

Based on the establishment of the mathematical model of CCD camera noise described above, a simulation platform for CCD camera system noise model was developed using MATLAB software for simulation analysis. The operation interface is shown in Fig.4. For dark current noise, CCD dark current noise is 320e$^-$/s, and exposure time is 0.3s. For reset noise, absolute temperature is 20°C, output capacitance is 20fF. For quantization noise, CCD full well charge capacity is 100000e$^-$, ADC quantization bit is 16 bits. For off-chip amplifier noise, input voltage is 2.9nV, R_f is 2000Ω, R_g is 100Ω, R_s is 100 Ω, the in-phase input current is 13pA, and the inverted input current is 1.5pA. The on-chip amplifier noise is 4.7e$^-$. The noise at normal temperature is 10.4567e$^-$[7].

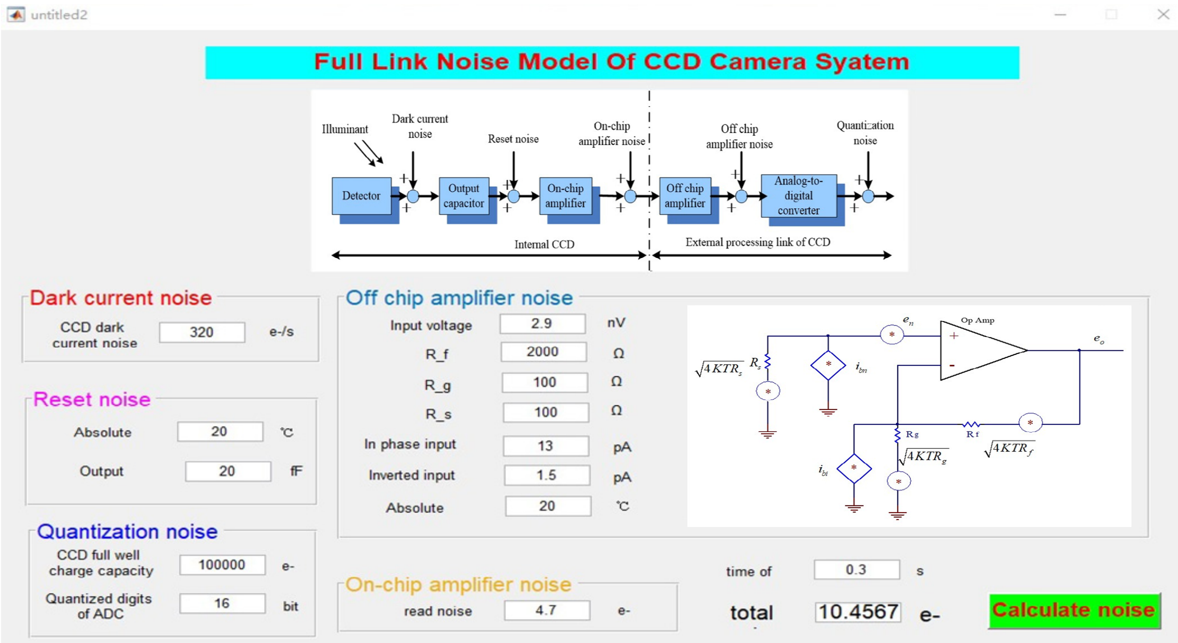

Figure 4. The operation interface of full link noise model of CCD camera system

In addition, in order to verify the accuracy of the mathematical model, an indoor imaging experiment was conducted using a CCD camera. The electronic noise test is mainly used to evaluate the noise level of the entire imaging process from the CCD detector to the video processing circuit. The key is to shield the optical signal, and use the image signal collected by the ground inspection equipment to reflect the noise of the CCD itself and the noise introduced by the video processing circuit. Therefore, the test method here is to calculate the mean square root of the image to evaluate the noise level of the camera system for images in the CCD camera's test mode, namely, the noise signal of the CCD video processing link and the CCD background noise signal[8]. The detailed steps are as follows:

Step 1: Place the CCD camera in a dark room and cover the lens with a black cloth.

Step 2: Use the Image acquisition system to set the working mode of the CCD camera to the testing mode.

Step 3: In the testing mode, collect 100 images continuously, as shown in Fig.5, and average the 100 images. Use the following formula to calculate the root mean square σ of the image.

$$\sigma = \sqrt{\frac{\sum_{i,j=1}^{i,j=n}(DN_{i,j}-D\bar{N})^2}{n-1}} \tag{9}$$

$DN_{i,j}$ - output pixel gray value of image row i and column j

n - Number of rows and columns of the selected image

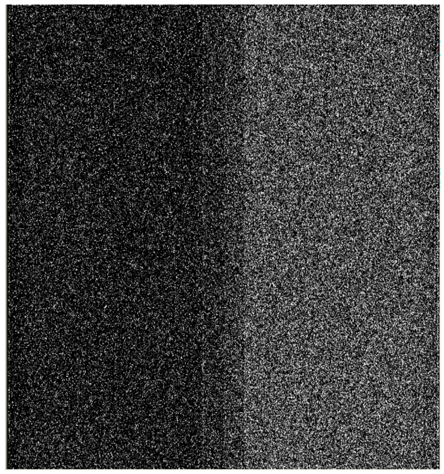

Figure 5. Images of the testing mode

Step 4: The camera system channel gain calculation model is shown in Fig.6. CCD output response sensitivity is expressed as $k = 4uV / e^-$, total gain of video link is described as $G_t = 10.626$, $V_{FSR} = 4V$, n=16, V_{FSR} =4V.

$$gain = \frac{\frac{V_{FSR}}{2^n}}{G_t \times k}(e^-/LSB) \tag{10}$$

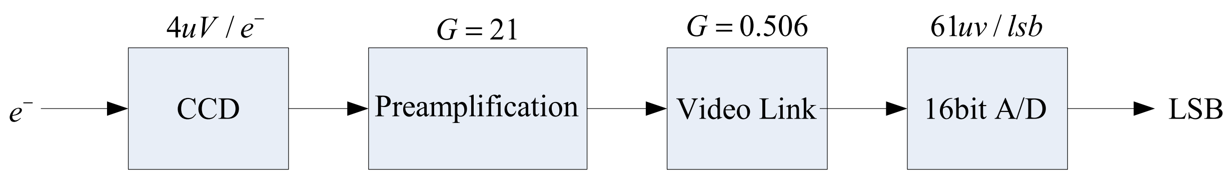

Figure.6 The camera system channel gain calculation model

Step 5: Calculate the camera system noise according to Equ.10 and obtain a readout noise of 10.32e$^-$ (@ 1MHz) for the camera system.

The simulation results of the CCD camera system noise model software are compared with the laboratory measured results, and the two results(10.4567 and 10.32) are basically consistent, verifying the correctness of the CCD camera system noise model.

5. CONCLUSION

Based on the analysis of the full link noise sources of CCD imaging systems, mathematical models of circuit noise are proposed, such as dark current noise, reset noise, on-chip amplifier noise, off-chip amplifier noise, and quantization noise. The established mathematical model of noise is simulated using MATLAB simulation software, and the simulation results can accurately calculate the noise level of a CCD imaging system, It can be used to determine whether the noise index of the camera system design meets the requirements. Finally, an experimental platform is built for testing. The experimental results show that the noise signal level simulated by the noise model established in this paper is very similar to the actual noise signal level, verifying the rationality of the noise model.

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