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Comparisons of the camera OECF, the ISO speed, and the SFR of digital still-picture cameras

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ABSTRACT

In this paper, the techniques as well as the measurement results of the performance of commercial digital still-picture cameras are presented. The key parameters such as the camera Opto-Electronic Conversion Function (OECF), the noise based ISO speed, and the spatial frequency response (SFR) are reported. The camera OECF is defined as the relationship between the input luminance and the grayscale or digital output from the camera, which was measured by using a test chart with twelve squares of various luminances. The ISO speed was calculated from the exposure time, the effective f-number, and the luminance at different incremental signal-to-noise ratios. In general, the exposure time is not obtainable from a commercial digital camera unless a destructive measurement is undergoing. In this study, a device was setup to obtain the exposure time when the OECF test chart was recording. A modified slanted-edge method was employed to estimate the SFR by imaging a pattern with a black-to-white edge tilted at an arbitrary angle. There are seven digital still picture cameras as our test samples whose CCD sensor contains VGA-size and million pixels. The camera OECF of these cameras did not show significant difference under a large range of illumination. However, the ISO speed and the SFR were of great variation.

Keywords: Digital still-picture camera, opto-electronic conversion function, incremental signal-to-noise ratio, ISO speed, spatial frequency response

1. INTRODUCTION

Digital still-picture cameras (DSC) using CCD or silicon CMOS area sensors have becoming a major product on the consumer electronic market. In a complex DSC system, the quality of acquired images is mainly affected by (1) the optics, such as the lens system for imaging and zooming, (2) the opto-electronic (OE) devices such as CCD area sensors, and (3) analog and digital electrical circuitry. In addition, various signal-processing algorithms such as data interpretation, color correction, image compression, etc. also influence the image quality in some way. For DSC manufacturers, it is important to understand and exactly characterize the camera performance in order to improve the image quality and design better, convenient usages to the cameras. For users, a simple and clear illustration to the camera will assist to purchase a proper camera to their needs.

However, it is difficult to provide a complete, satisfactory analysis of the performance of electronic still-picture camera because it is constructed by most part of the conventional film imaging cameras and an electronic microprocessor. ISO and many research groups have been working on standardizing the characteristics and test methods of digital still-picture cameras. The general characteristics of interest include the relationship of the optical input to the digital output level, the noise performance, the equivalent exposure speed, the spatial resolving capability, and the color performance. Each again cannot be fully described by a single function or parameter using a single method. In the ISO documents, some functions and various methods are defined for each characteristic in order to fit different camera organizations and test environments. Complete measurements of these characteristics would be tedious and unnecessary. In this study, we select an opto-electronic conversion function (OECF) method, an ISO speed, and the spatial frequency response (SFR) in the resolution measurement to evaluate the performance of commercial electronic still-picture cameras. There are seven cameras used for in this study: three have a million-pixel CCD sensor, Case 1 to Case 3, and four have a VGA-size CCD sensor, Case 4 to Case 7. Limited to the source of digital still-picture cameras, this research does not intend to provide a

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performance benchmark. Our goal is to develop effective and simple methods to precisely characterize the digital still-picture cameras, to improve their performance, and to develop various functionalities of digital cameras based on the techniques presented in this report. Some other works can be referred at the references [1]-[3].

2. CHARACTERISTICS OF DIGITAL STILL-PICTURE CAMERAS

2.1 Opto-Electronic Conversion Functions (OECF's)

In ISO14524 [4], the opto-electronic conversion function (OECF) is defined as the functional relationship between the optical input and the digital output signal level of a digital still-picture camera. The measurement of the OECF's is fundamental because it is required for the development of digital cameras and for the calculations of other characteristics such as the ISO speeds and the spatial resolution. Besides, it will be used for data correction for other digital still-picture camera characteristics and may be helpful in the processes of digital image data.

Although analog terminologies, such as the "H&D" curve for photographic films and the "gamma" curve for CRT monitors, are widely used, the OECF's are necessary because none of these methods can be easily or unambiguously applied to electronic still picture cameras. In digital systems, the sampling and quantization processes present fundamental issues that need to be addressed in a standardized manner. The flexibility of digital systems complicates the determination and presentation of the functional relationship between the camera's optical input and digital output signal level. Therefore, ISO 14524 attempts to account for all the variables and assure that results are presented in consistent fashion.

There are three OECF's defined in ISO 14524. The first is the camera OECF that is accomplished by using the camera system to capture an image of the chart under controlled conditions. Then, the focal plane OECF involves the exposure of the electronic still picture camera sensor directly to specific quantities of uniform illumination with the camera lens removed. The alternative focal plane OECF is introduced for the measurement of focal plane OECF under the circumstances that a particular electronic still picture camera does not allow the lens to be removed. It is suggested that the focal plane OECF to be reported mainly because the focal plane OECF provides the optical-input-to-digital-output relationship of the camera part including the sensor and the signal processing electronics. It behaves quite differently from the optical image formation part which converts scene into image and is scene dependent. This tends to be highly non-linear and complicates further analysis. We therefore prefer to analyze these two parts separately. However, the mandatory automatic exposure control and the fixed imaging lens system found in lots of digital cameras preclude the determination of focal plane OECF.

2.2 ISO speeds

The ISO speed rating is an important reference of photographic systems in order to guide the users to set a proper exposure when taking a photograph. Many factors affect the camera exposure including the exposure time, the iris aperture, the lens transmittance, the illumination, and the scene reflectance [5]. Using an insufficient exposure to obtain an image could result in a noisy image for the electronic gain being applied automatically. On the other hand, if the exposure exceeds a certain amount, says the saturation of camera sensors, the image becomes bloom in the bright areas and blur on the edges. The contrast is also decreased. With the help of the ISO speed ratings, the user can set proper exposures and the manufacturers can provide more functional settings to the exposure control of the cameras.

An ISO speed rating is intended to serve as a guide to photography. The ISO speed rating for an electronic camera should directly relate to the ISO speed rating for photographic film cameras. For example, if an electronic camera has an ISO speed of ISO 100, then the same exposure time and aperture be appropriate for ISO rated film / process system. However, differences exist between electronic and conventional film cameras. Electronic cameras have a range of ISO speed ratings because the best quality of image can be achieved by varying the electronic gain and by performing signal processing algorithms after the image is captured. In ISO 12232, this range is defined as the ISO speed latitude.

Two types of the ISO speed are defined: Saturation based speed and noise based speed. The later speed is preferably used to indicate the camera's underexposure latitude, and the former speed value is preferably used to the camera's overexposure latitude. Since the camera view depth is enhanced when the exposure is lower, the noise based value is preferably determined for most electronic cameras. In this report, the noise based ISO speeds of several electronic cameras were presented.

2.3 Resolution measurement

The spatial resolution metrics, the test methods, and the test charts were standardized in ISO 12233 [6]. The spatial resolution capability, one of the most important attributes, of an electronic still picture camera is the ability of the camera to capture fine details found in the original scene. For electronic still picture cameras the resolving ability depends on many factors, including the performance of the optical imaging lens system, the number and the pitch of camera sensing photodetectors, as well as the electrical circuits. The functions of the electrical circuits in camera include the gamma correction function, digital interpretation, color correction, and the image compression.

Different measurement methods can provide different metrics to quantify the resolution of an electronic camera. These metrics contain visual resolution, limiting resolution, spatial frequency response (SFR), modulation transfer function (MTF), optical transfer function (OTF), and aliasing ratio. In ISO 12233, a resolution test chart is designed to evaluate the resolving performance of an electronic camera. The visual resolution is subjectively judged based on vertical, horizontal and diagonal hyperbolic wedges oh the test chart. These patterns should be enlarged by integer multiples on a hard copy and then reproduced on a monitor or a printer to ensure that the measurement value is not reduced due to the different resolution between the test camera and the output device. The limiting resolution is determined by calculations of the resolution response of vertical and horizontal square wave sweeps on the test chart. The spatial frequencies of the square wave sweeps vary from 1/100 to 1/1000 of the height of the test chart. The value (in the unit of line-widths-per-picture-height, or LW/PH) is found at the location where the resolution response of the square wave is equal to 5% of the reference response. The two resolution metrics described above can only obtain discrete measurements on certain spatial frequencies provided by the test chart. The SFR measurement provides an overall frequency response of an electronic camera by capturing an image of a test pattern that contains a square tilted at a small angle. A computer then analyzes the image data, consisting of a tilted black-to-white edge, by using a standard SFR algorithm.

In this report, the spatial frequency response (SFR) was evaluated by using an algorithm that applies the same concepts as the ISO standard SFR algorithm. The algorithm adopted here can be applied to any test pattern containing black-to-white (and white-to-black) edge tilted at arbitrary angles, although it is optimized for the tilt angle between 10 to 25 degrees. Moreover, the method has high reliability even for an image of a low S/N ratio such as 5. Therefore, it is preferably adopted at a laboratory or a production line where precise alignment equipments cannot be used.

3. CHARACTERISTICS MEASUREMENTS OF ELECTRONIC STILL-PICTURE CAMERAS

3.1 Measurements of the camera OECF

In this study, the camera OECF's of some commercial electronic cameras were measured. The camera OECF is selected because of not only the reasons discussed in Sect. 2.1 but also some practical issues. The measurement of the camera OECF includes the effects of the camera lens and associated flare, while focal plane OECF's do not. With the image formation effects vary with the overall scene luminance ratio, this variability can quite large, and consequently it is possible to determine a repeatable camera OECF only for a specific scene, such as a test chart. Most digital still picture cameras do not allow the lens to be removed. The mandatory automatic exposure control found in some cameras precludes the determination of Focal Plane OECF's. Since the optical image formation stage is not removed, a test chart recording enough scene variations is imaged onto the camera sensor and the camera OECF is then obtained by analyzing the test-chart image. The whole processes are accomplished in one exposure, unlike many exposures are needed when the focal plane OECF is measured. The sensor illuminance shall be assumed to be as calculated from the following equation:

$$E_s = \frac{0.65 \times L_t}{A^2}, \tag{1}$$

where E_s is the illuminance in lux falling on the sensor, L_t is the arithmetic mean luminance of the target in candelas per square meter, and A is the effective f-number of the lens. Figure 1 shows a Camera OECF Test Chart, similar to the Camera OECF Test Chart designed by ISO, simulating the image formation effects produced by a scene with a specific luminance ratio and average distribution of luminances. In the test chart, there are twelve squares with neutral reflectivities varying from low to high, and each square represents a luminance value measured directly using a photometer. A thin stick driving by a stepping motor in the middle of the chart is used to estimate the exposure time. This chart is also used to determine the incremental signal-to-noise ratio and the ISO noise based speed discussed in the next section.

To determine the camera OECF, images of the test chart were recorded for computer to proceed calculations. At each test,

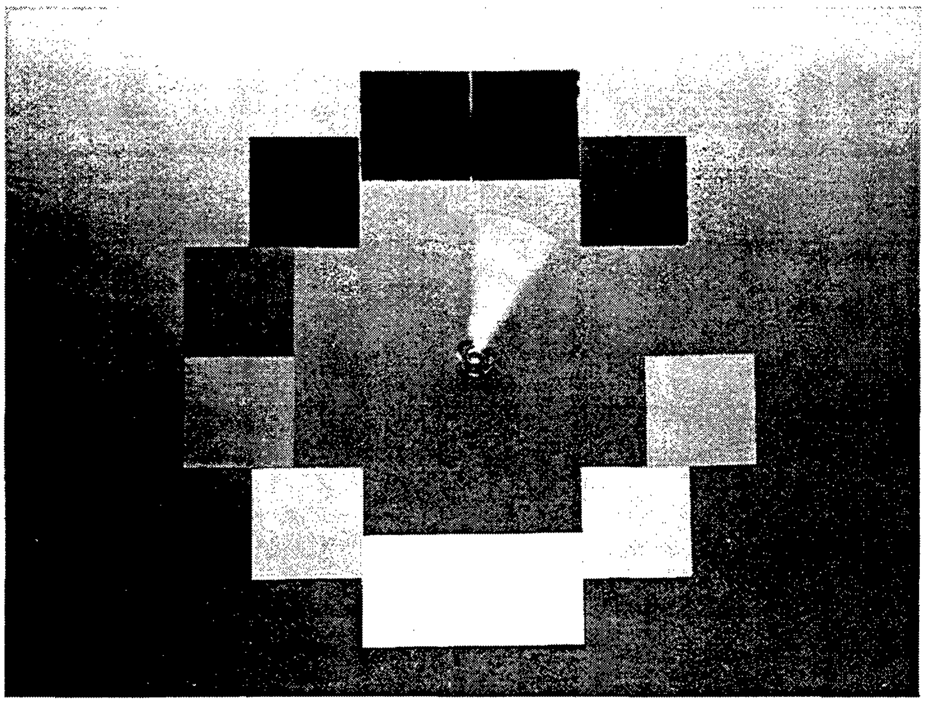
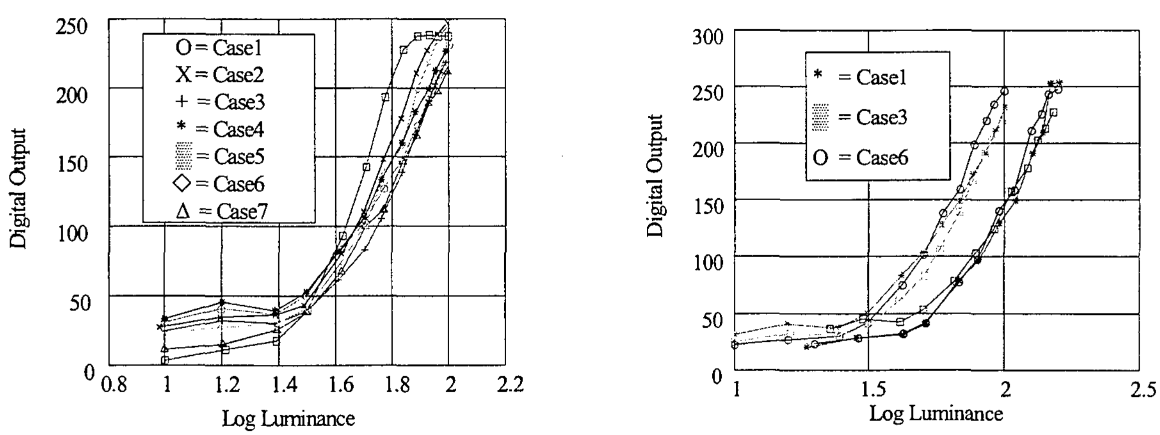


Figure 1. The image of the Camera OECF Test Chart

ten trials were taken in order to minimize random noise appearing at each exposure. For each trial, the mean digital output level was determined from a 64 by 64 pixel area located at the same relative position in each image. The 64 by 64 pixel area shall be located at the center of the test block. The final digital output level data presented is the mean digital output levels for all the trials. The input luminance was measured using PR-650 SpectraColorimeter.

The measurement of the camera OECF's of the seven test cameras are shown in Fig. 2(a). Limited to the light source in our lab, most cameras did reach their saturation except Case 5. Notice that the automatic electronic gain increases the output digital level as well as noise under the underexposure condition. Hence the digital levels of the dark areas are increased significantly. When the saturation is reached as Case 6, the dark area does look 'dark' because the electronic



(a) (b)

Figure 2. (a) The camera OECF of the digital still-picture cameras and (b) the camera OECF's measured at different illuminations

gain did not enlarge the output level as in the other cases. However, the saturation of Case 6 only provides an output level of 240, far below the general saturation output at 255. Figure 2(b) shows two sets of the camera OECF's measured at two illuminances in which the largest luminances from the bright square are about 160 and 100 cd/m^2, respectively. The measured electronic gains are larger than 1 in this figure although the optical input was increased by 80%. This phenomenon could be improved by incorporation a contrast enhancement method with the auto-exposure process in the signal processing unit.

3.2 Measurements of the noise based ISO speed

In many photographic applications, it is desirable to use the highest exposure index (lowest exposure) possible, in order to maximize the depth of field, minimize the exposure time, and offer the maximum acceptable latitude for exposure of image highlights. The noise based ISO speed serves as the exposure index that provides an appropriately low noise image for typical electronic camera applications. Two different noise based speeds are determined, one that provides the "first excellent" image and a second that provides that provides the "first acceptable" image.

The noise based speed, S_{noiseX}, can be obtained using either the focal plane method or the scene luminance method. The later is adopted in this study. In this method, the ISO noise based speeds are determined from the scene luminance required to produce specific image incremental signal-to-noise ratio values using the following equation:

$$S_{noiseX} = 15.4 \times \frac{A^2}{L_{S/N} \cdot t_s}, \qquad (2)$$

where A is the effective f-number of the taking lens, t_s is the photosite integration time, and $L_{S/NX}$ is the luminance that provides a camera signal-to-noise ratio, S/NX, satisfying the following criterion:

$$S/N = \frac{L_{S/N} \times g(L_{S/N})}{\sigma(D_L)}. \qquad (3)$$

Here, S/N is the signal-to-noise ratio of the value X, $L_{S/N}$ the luminance in cd-m^{-2}, $g(L_{S/N})$ the incremental gain (the rate of change in the mean output level divided by the rate of change in the input luminance), and $\sigma(D_L)$ the standard deviation of the monochrome output level values (for monochrome cameras) taken from a 64-by-64 pixel area. Note that $S_{noise42}$ denotes the noise based speed measured at S/N equal to 42, and is designated to the "first excellent" image quality; $S_{noise10}$ denotes the noise speed measured at $S/N = 10$, and is designated to the "first acceptable" image quality.

The value of $L_{S/N}$ was determined by plotting the incremental S/N as a function of the luminance L and estimating the value that produces an incremental S/N value equal to 42 for $S_{noise42}$ and 10 for $S_{noise10}$. The plot of incremental S/N to L was obtained using the same test chart as used in the measurement of the camera OECF. $\sigma(D_L)$ was determined as the standard deviation of the pixel values in each 64-by-64 area selected foe the camera OECF. The incremental gain $g(L_{S/N})$ was also obtained from the camera OECF by using the equation

$$g(L_j) = \frac{OL(L_j) - OL(L_j - \Delta L_{i,j})}{2\Delta L_{i,j}} + \frac{OL(L_j + \Delta L_{j,k}) - OL(L_j)}{2\Delta L_{j,k}}, \qquad (4)$$

Table 1. Noise based ISO speed of the digital still-picture cameras

Case No.	1	2	3	4	5	6	7
$S_{noise10}$	320	640	800	400	160	640	320
$S_{noise42}$	100	50	64	64	100	250	160

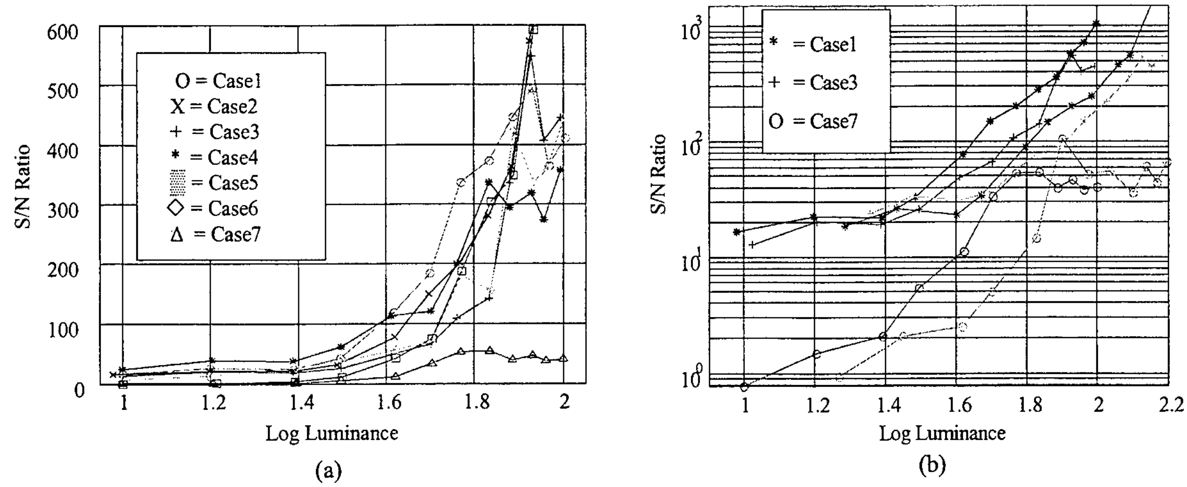


Figure 3. (a) The incremental signal-to-noise ratio of the digital still-picture cameras and (b) three incremental signal-to-noise ratio measurements at different illuminations (L1=100 cd/m^2 and L2=160 cd/m^2)

where *OL* and $\Delta L_{i,j}$ are the digital output level and the change in luminance between luminance L_i and luminance L_j, respectively.

The noise based ISO speed was calculated by Eq. (2) in which the integration time was estimated using the clock-like timing stick in the Camera OECF Test Chart as shown in Fig. 1. The stepping motor was driving by a clock period of 1.4 ms and it took 200 steps for a cycle (360°). The stick rotated about 30° during the exposure which is equivalent to an integration time of 23.3 ms. The noise based ISO speed obtained from the measured values are listed in Table 1. Note that the speed value in Table 1 is determined by referring to Table 1 of ISO 12232 in which the results from Eq. (2) were assigned to a specific ISO rating for a certain range of the calculated values. For example, if an S_{noiseX} = 116.5 is calculated, then the speed rating of ISO100 D should be reported for this S_{noiseX} being the range of 100 through 125. The letter 'D' denotes that the measurement was taken using a daylight illumination. Figure 3 shows the incremental signal-to-noise ratio of the test cameras. The incremental *S/N* is increased as the input luminance increased as expected. Because there are many factors to influence the incremental *S/N* ratio, it is impossible to provide a clear analysis unless the effects of individual processes in a digital camera can be measured. However, the extremely large *S/N* values observed in Fig. 3(b) are referred to the camera blooming phenomenon due to the sensor saturation.

3.3 Measurements of the SFR

Spatial frequency response (SFR) is one of the most important characteristics of digital still cameras, which describes the capability to resolve the spatial details of images generated from incoming optical information. The algorithm adopted first estimates the angle of a tilted edge, computes the edge spread function (ESF) using the curve fitting technique, gives the line spread function (LSF) by differentiating the ESF, and finally generates the SFR by Fourier transforming the LSF. The advantage of this algorithm is that it can be applied to any test chart containing edges slanted at arbitrary angles and provide high accuracy of the SFR measurements of commercial still-picture cameras. Figure 4 shows the SFR Test Chart used in this study that contains nine chessboard-like patterns and each consists of four squares, two in black arranged in diagonal and two in black arranged in back diagonal. This arrangement is designed to provide horizontal as well as vertical edges changing both from back to white and white to black in a small area on the chart for measuring the ECF of an imaging camera. Without necessarily knowing the tilted angle of a particular test chart in advance or using precise alignment between the test chart and the camera, this algorithm can easily be used both in the lab and in the field. The details of the developed algorithm and its performance analysis are presented in another paper presented in this conference.

The SFR's of the digital cameras are shown in Fig. 5. The results are consistent with the theory that the smaller the pitch between the sensor pixels, the larger the cutoff spatial frequency. The cameras of Case 1 and 3, both having a 1/3" million-pixel CCD sensor, have the smallest pixel pitch (about 6 microns) and have the largest cutoff frequencies.

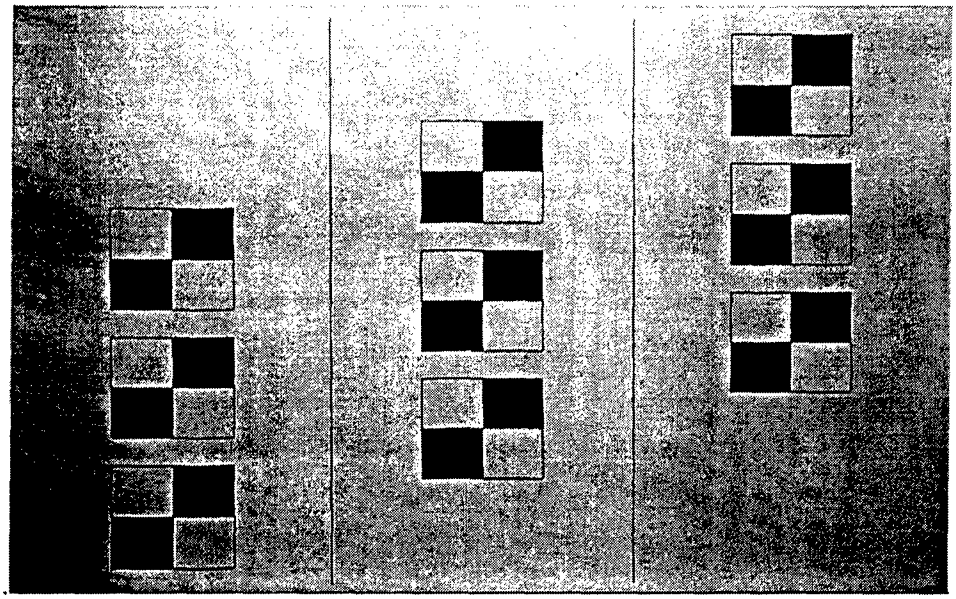


Figure 4. The image of the SFR Test Chart

Although there are many possibilities that Case 1 might have a better SFR than that of Case 3, one thing is for sure that the optics of Case 1 is more delicate. Case 2 is also a million-pixel digital camera but with a 2/3" CCD sensor and large pixel pitches. It has a poor cutoff but the SFR is almost as good as that of Case 3, and this might be due to the delicate optics on Case 2. Moreover, the SFR of Case 2 is better than those of all the VGA-size cameras. The reason that Case 5 has the worst SFR is because at the moment we used the Case-5 camera to photograph the SFR Test Chart, the condition of the camera became worse than it first came to our lab. The images were barely clear and its electronics did not function well.

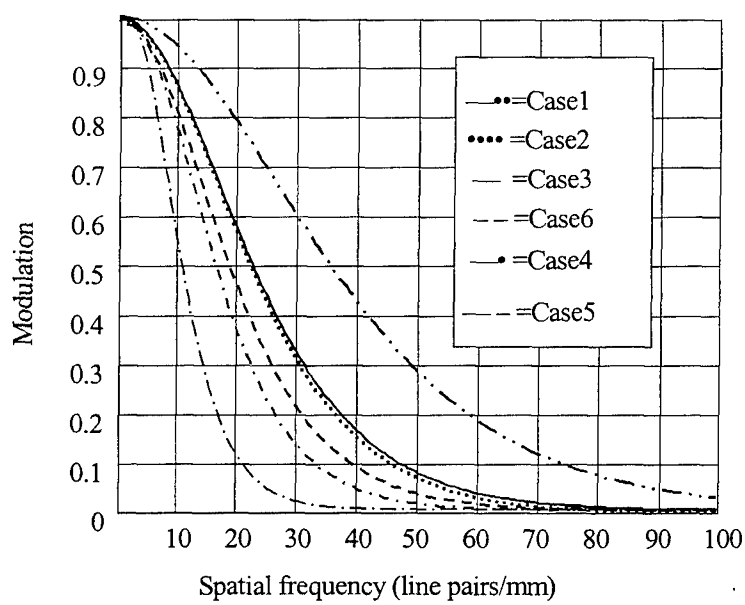


Figure 5. Spatial frequency response of the digital still-picture cameras

4. CONCLUSIONS

We have presented the measurement results of the camera OECF, the incremental signal-to-noise ratio, the noise based ISO speed, and the SFR of seven digital still-picture cameras. There is no significant difference in the measured OECF's, the incremental signal-to-noise ratios, and the noise based speeds regarding to different components and structures of these cameras. It might be due to the electronics for signal processes greatly smooth the variations from different components. The influence of the electronics needs further researches and is not known for this moment. The characteristics that can be used to distinguish the performance of a digital camera will the SFR. However, the units used in the SFR, i.e., line pairs per mm, will mislead user. A more proper unit that is easily understood will be necessary in the future.

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