Forward-reverse Motion’s Influence on CCD Detector’s Imaging Quality

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ABSTRACT

The relative motion to the CCD camera during the imaging course is becoming more and more prevalent. Especially when the objects are moving forwards or backwards at a high speed, the image’s resolving power will decline rapidly from the center to the edge of each frame, which will deteriorate the imaging quality seriously. On the problem, in view of the use of grating with sine distributed intensity in the evaluation of static system’s imaging quality, and considering that during the objects’ forward-reverse motion, the magnification of optical image of the object is changing smoothly, a model of concentric circles with sine distributed intensity is built on the area CCD’s photosensitive surface, the contrast of which is 100%. Using the concentric circles model, the paper has deduced the signal intensity and contrast expressions of each frame image during the objects’ relative motion. Then the CCD detector’s imaging quality can be evaluated by the signal intensity and contrast of each frame image.

From the expressions, we can know that the concentric circle’s radius, the object’s spatial frequency’s change rate and CCD’s integration time will all influence the image’s resolving power. Whichever parameter of the three increases, the contrast will decline by the function of |sinc|.

On the basis of the theoretic analyse, the paper has given some pictures and graphs of the experimentation. The calculating data and pictures from the experimentation have verified the results of the theoretic analyse.

Keywords: Model of Concentric Circles, Forward-Reverse Motion, area CCD, Contrast of Image, spatial frequency.

1. INTRODUCTION

With the popularization of CCD cameras, imaging of moving objects is widely used in many fields, such as airphoto, military reconnaissance, high-speed imaging guidance, tracking imaging, remote sensing, industrial television and so on. Under these circumstances, the influence of objects’ forward-reverse relative motion on the camera, which results from the imaging mechanism of CCD itself, is becoming a great challenge to the imaging quality during the imaging process.

At present, most of the researches are developed on object’s vertical and horizontal motion. However, in the practical imaging processes, it is much prevalent that the objects move forwards and backwards relatively to the camera. Under these circumstances, the magnification of the object’s optical image on CCD’s photosensitive surface is changing smoothly and the image degeneration resulting from the shooting process above-mentioned is particular. On the problem,
the paper studies the principle of image degeneration and the evaluation methodology of CCD’s imaging quality.

2. MODEL OF IMAGE DEGENERATION OF AREA CCD

Because of the complexity and diversity of the moving objects, it is essential to select a representative moving object and build a shooting process model for the representative moving object and the CCD camera system. As thus we can evaluate the imaging quality of the CCD camera system effectively and conveniently.

2.1 Selection of representative moving object

The grating stripes with different spatial frequencies and sine or black-and-white distributed intensity are popularly used in evaluating the static image’s resolving power \(^{[1,2]}\). Considering that during the objects’ forward-reverse motion, the magnification of optical image of the object is changing smoothly and the images with the central fixed are centrosymmetric, a model of concentric circles stripes with sine distributed intensity is established, the contrast of which is 100%, as shown in Fig. 1\(^{[2]}\).

![Fig. 1 The model of concentric circles stripes with sine distributed intensity](image)

Taking the center of the concentric circles as the origin of coordinates, a polar coordinate system is built, as is shown in Fig. 1. When the object is static, the object’s intensity distribution on the radius can be denoted as follows:

\[
E(r,t) = E_0 (l + \sin 2\pi f r)
\]  

(1)

Where \(r\) is the radius of the concentric circles, \(f\) is the spatial frequency of the object, \(f = 1/\lambda\).

In this paper, it is supposed that the object is infinite in area, so that the area CCD could be entirely covered by the optical image of the object. And the optical axis of the camera system drills through the center of the object and is perpendicular to the object’s surface.

2.2 Imaging model during the object's forward-reverse motion to the camera system

Fig. 2 shows the imaging model during the object's forward-reverse relative motion to the camera. Supposing that in the course of the object's forward-reverse relative motion, the object's center is coaxial with camera system, and the object's optical image can entirely cover the CCD photosensitive surface throughout the imaging process.

The meanings of the parameters in Fig. 2 are as follows:

- \(H_1, H_2, H\): Sizes of the object's parts which are covered by the camera's viewing field at different moments;
- \(h\): Size of the CCD sensitive surface;
\( F \): Focal length of the lens;

\( S_1, S_2, S \): Object distance at different moment, \( S_1, S_2, S \gg F \), this means the object moves in the range of the camera's depth of field;

\( S' \): Image distance;

\( \lambda \): Spatial periods of the object (see Fig. 1);

\( \lambda' \): Spatial periods of the object's optical image on CCD's photosensitive surface;

\( f \): Spatial frequency of the object, \( f = 1 / \lambda \);

\( f' \): Spatial frequency of the object's optical image on CCD's photosensitive surface, \( f' = 1 / \lambda' \).

In Fig. 2, when the object is moving uniformly from \( S_1 \) to \( S_2 \), the duration of the object’s motion is \( \tau \), the speed of the object \( v_s \) can be written as follows:

\[
v_s = (S_2 - S_1) / \tau
\]  

(2)

Obviously, if \( v_s \) is positive, the object moves away from the camera; contrarily it means the object is moving close to the camera if \( v_s \) is negative.

![Imaging model with the lens' focal length (F) fixed when the object is moving forwards or backwards to the camera.](image)

During the object’s motion, the object distance at the moment \( t \) (\( 0 \leq t \leq \tau \)) can be written as:

\[
S = S_1 + v_s \cdot t
\]  

(3)

From Gauss formula in the geometric optics, we can obtain the following expression:

\[
h = \frac{H \cdot S'}{S} = \frac{H \cdot F}{S - F}
\]  

(4)

At the moment \( t \), the amount of the optical image’s spatial periods (i.e. the mount of the object’s spatial periods which are in the camera's viewing field) can be calculated as

\[k = H / \lambda \]  

(5)

Then the spatial periods of the object’s optical image on the CCD’s photosensitive surface can be obtained:

\[
\lambda' = \frac{h}{k} = \frac{\lambda \cdot F}{S - F} = \frac{\lambda \cdot F}{S_1 - F + v_s \cdot t}
\]  

(6)

And the spatial periods’ change rate of the object’s optical image is determined by

\[
v_{\lambda'} = \frac{d\lambda'}{dt} = -\frac{\lambda \cdot F \cdot v_s}{(S_1 - F + v_s \cdot t)^2}
\]  

(7)

The spatial frequency’s change rate of the object’s optical image also can be obtained:
From (7) and (8), we can know that when the object moves uniformly forwards or backwards to the camera (i.e. the object’s speed is a constant of time) and the focal length of the camera lens \( F \) is fixed, the change rate of the spatial periods of the object’s optical image on CCD’s photosensitive surface \( v_{\lambda} \) is a function of the time \( t \) (i.e. the rate is changing during the object’s motion), but the change rate of the spatial frequency of the optical image \( v_f \) is a time constant (i.e. the spatial frequency is changing uniformly).

On the basis of the deduction above, a model of concentric circles with sine distributed intensity, the spatial frequency’s change rate of which is a time constant, is directly built on the CCD’s photosensitive surface. This method can simplify the research on the evaluation methodology of image quality and the principle of image degeneration by taking no account of the differences among complex optical systems of the cameras.

During the object’s moving process, the optical images’ beginning spatial frequency is represented by \( f_0 \), the final is represented by \( f_1 \), and the duration of its change is represented by \( \tau \). While the spatial frequency is changing uniformly, the change rate of spatial frequency can be expressed as:

\[
v_f = \frac{f_1 - f_0}{\tau}
\]

If \( f_1 > f_0 \), \( v_f > 0 \), the concentric circle stripes of the optical image on the CCD become dense; Contrarily, \( f_1 < f_0 \), \( v_f < 0 \), the stripes become sparse.

If the CCD’s frame period is represented by \( T_k \) (ms), the intensity distribution of the nth frame optical image on the CCD’s photosensitive surface can be calculated by the following expression:

\[
E(r, n, t) = E_0 \left[ 1 + \sin \left( 2\pi \left( f_0 + v_f (n - 1)T_k + v_f t \right) \right) \right], \quad 0 < t \leq T_k, \quad 0 < nT_k + t \leq \tau
\]

where \( t \) represents any moment between the beginning and the end of a frame’s exposure time.

Representing the integral time of the CCD’s photosensitive surface with \( T_e \), the intensity distribution of the nth frame of integral image on CCD is obtained by calculating the integral of (10):

\[
I(r, n, T_e) = \alpha \int_0^{T_e} E(r, n, t) dt
\]

\[
= \alpha E_0 T_e \left[ 1 + \sin(\pi r \cdot v_f \cdot T_e) \cdot \sin(\pi r \left[ 2(n - 1)T_k + T_e \right] v_f + 2f_0) \right]
\]

where \( \alpha \) is a constant related to CCD’s characteristics.

From (10), we can know that the intensity of the CCD’s integral image is still sine distributed, but the magnitude is modulated by the function sinc.

For the CCD’s integral image’s sine distributed intensity, the contrast of the image can be used to evaluate CCD’s imaging quality. The contrast of an image is defined as follows:

\[
V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \left| \sin(\pi r v_f T_e) \right|
\]

where \( I_{\text{max}} \) and \( I_{\text{min}} \) are the max. and min. of the image’s signal intensity in one spatial period along the radius respectively.

It can be obtained from (12) that the radius of the concentric circle \( r \), the spatial frequency’s change rate of the
optical image on CCD \( v_f \) and the CCD’s integral time \( T_c \) will all influence the distribution of the integral image’s contrast. The magnitude of the contrast, which reaches the maximum at the center of the image, will decline by the function \(|\text{sinc}|\) along the radius. When \( v_f \) or \( T_c \) increases, the distribution of the image contrast will also decline by the similar rule.

### 3. EXPERIMENTS AND RESULTS

Using the model of concentric circles with sine distributed intensity above-mentioned, a program has been built to calculate the images’ signal and contrast. And some calculating data and pictures will be given in this section.

By changing the parameters in the expressions (11) and (12), we can obtain integral images’ signal of different degeneration degree and the images’ contrast curves. For the images are centrosymmetric, we only need to calculate the signal intensity along the radius for each frame image\(^3\).

#### 3.1 Integral images’ intensity distribution along the radius

When the integral time \( T_c \) is 20ms, the optical image’s beginning spatial frequency \( f_0 \) is 50TVL, the final spatial frequency \( f_1 \) is 200TVL, and the duration of the spatial frequency’s change process \( \tau \) is 300ms and 500ms respectively, the change rate of the optical image’s spatial frequency \( v_f \) equals to 472.2TVL/s and 283.3TVL/s, respectively. Two frame of images (the 1st and the 10th frame images) and their intensity distribution graphs are given in Fig. 3 and Fig. 4.

(a) The object’s optical image (left) and the CCD’s integral image (right), \( t=20\)ms, the 1st frame.

(b) The object’s optical image (left) and the CCD’s integral image (right), \( t=200\)ms, the 10th frame.

(c) The intensity distribution curves of the 1st (\( t=20\)ms) and 10th (\( t=200\)ms) image.

Fig. 3 The object’s optical images and the CCD’s integral images and the intensity distribution of the CCD’s integral images. (The duration of the spatial frequency’s change process \( \tau \) is 300ms)
From the pictures and graphs in Fig. 3 and Fig. 4, we can know: the contrast of the CCD’s integral images, which reaches the maximum in the center of the image, declines gradually along the radius (in another word, the center of the image is most clear-cut, and the region of the image away from the center becomes blurry); but the outlines of the CCD’s integral images’ intensity distribution curves are coincident (i.e. the clarity degree of a pixel in the image is invariable), what is changing is only the images’ spatial frequency, as is shown in Fig. 3 and Fig. 4. For these, it can be explained as follows: When the optical image’s spatial frequency is changing uniformly at the rate of \( f_v \) (TVL/s), whatever the spatial frequency increases or decreases, the moving speed of a point in the image is increasing with the radius’s extension. But the moving speed of a point at a certain radius is related with the image’s spatial frequency \( f \). If \( f \) increases, the point’s speed at this radius will decline. Thus during the imaging process, the profiles of the CCD’s integral images’ intensity distribution curves are invariable and the distribution of the definition of the CCD’s integral images is independent of the time and the image’s spatial frequency.

Comparing Fig. 3 and Fig. 4, we see that when the duration of the spatial frequency’s change \( \tau \) is diminished, i.e. that the change rate of the spatial frequency increases, each point’s contrast on the integral image will greatly decline, which will induce the details in the edge of the integral image lost, as is shown in Fig. 3.

### 3.2 Spatial frequency’s change rate’s influence on CCD’s imaging quality

Taking the CCD’s integral time \( T_i = 20 \) ms, the change rate of the spatial frequency \( v_f = 300, 500, 800 \) and 1000TVL/s respectively, we can obtain the contrast curves of the corresponding integral images (see Fig. 5).
Fig. 5. The contrast curves of the integral images when $v_f$ equals to different values.

From the curves in Fig. 5, it is obvious that the more quickly the spatial frequency changes (i.e. the more quickly the object moves), the more rapidly the contrast of the integral images decline along the radius. When $v_f = 1000$TVL/s and the radius $r$ is greater than 55 pixels, the image’s details can’t be discerned.

3.3 Integral time’s influence on CCD’s imaging quality

While taking $v_f = 450$TVL/s, the CCD’s integral time $T_c = 2ms$, 8ms, 15ms and 20ms respectively, the contrast curves obtained are shown in Fig. 6.

(a) The object’s optical image (left) and the CCD’s integral image (right) when $T_c = 2ms$
(b) The object’s optical image (left) and the CCD’s integral image (right) when $T_c = 8ms$
(c) The object’s optical image (left) and the CCD’s integral image (right) when $T_c = 15ms$
(d) The object’s optical image (left) and the CCD’s integral image (right) when $T_c = 20ms$
Fig. 6. The object’s optical images and the CCD’s integral images with different integral time.

From Fig. 6, we can see: when $T_c=2$ms, the contrast at the edge of the integral image approaches 100%, but the image is too dark to discern (see Fig. 6 (a)); when $T_c=8$ms, the contrast at the edge declines distinctly and the image is dim (see Fig. 6 (b)); and when $T_c=15$ms or 20ms, the contrast declines more quickly but the average intensity is greatly improved. This means that reducing the integral time can increase the image’s contrast but will weaken the image’s average intensity.

It is worthy of notice that along the radius, the contrast declines at first, and after it decreases to zero, it will increase, then decrease, and so on (see Fig. 5 and Fig. 6). This is because the intensity distribution of the concentric circles model is periodic along the radius. After the contrast decreases to zero at the first time, the images’ details have already been lost completely.

4. CONCLUSION

When the objects are moving forwards or backwards to the CCD camera, the spatial frequency of the concentric circles’ optical image on CCD’s photosensitive surface is changing uniformly. Therefore we select the model of concentric circles built on CCD’s photosensitive surface as the moving object, the spatial frequency’s change rate of which is a time constant. Here the spatial frequency is changing uniformly means that during the imaging process, the reciprocal of the optical image’s magnification is changing uniformly.

During the imaging process, the CCD’s integral time, the change rate of the optical image’s spatial frequency (corresponding to the object’s moving speed) and the size of the CCD detector (corresponding to the maximum of the radius in the paper) will all influence the CCD detector’s imaging quality by certain laws. The paper has deduced the relations between the CCD’s imaging quality and the parameters above and given the corresponding calculating results. From the expressions and the calculating results, we find that both the image’s signal intensity and contrast are modulated by the function sinc. The influence law of the parameters’ on the integral image’s contrast can also be obtained quantificationally. Furthermore, by using the model of concentric circles presented in the paper, the CCD camera’s imaging quality can be evaluated effectively by the integral image’s contrast.
REFERENCES

