e2v

e2v technologies

Technical Note on the MTF of CCD Sensors

A unique MTF cannot be defined for a CCD using the mathematical structure of the classical theory, which is only applicable to linearly and uniformly responding devices with spatially continuous image surfaces.

The periodic, pixellated, structure of the CCD sensor surface samples any input image at a fixed spatial frequency. This creates **aliasing** and destroys the spatial continuity of test images employed to define the MTF.

All MTF data related to a CCD, or any periodically structured device, should only be used for system design or device comparisons with extreme caution.

However by specifying and declaring a detailed measurement procedure an 'operational' definition of a **(pseudo**) MTF can be devised. This allows repeatable measurements to be made.

Such measurements can be compared with confidence and if used with care and a declared qualification, they can provide useful guidance for both CCD quality control and system design.

INTRODUCTION

General

The MTF performance achieved at the output of a CCD is determined by:

(a) CCD device type
(b) Quality of manufacture
(c) Test conditions
(d) Actual MTF measurement procedure.

Clearly the MTF specification for a given CCD device type must define all the significant test conditions and the exact procedure to be employed. The MTF data provided by diligently executing the specified procedures may then be used for device quality (relative) assessment.

However extending the use of such data to system design, e.g. by convolving it with the MTFs of other system components, should only be done with extreme caution.

Comparison of MTFs measured using different procedures will probably be futile. This is because there is no unique MTF for an imaging sensor comprising an array of discrete light sensing elements (pixels) such as a CCD.

CCD Device Types

The achievable MTF performance is controlled by a large number of design features including:

(a) Front or back surface illumination
(b) Anti-reflection coatings on the silicon[a]
(c) Back surface recombination treatment[a]
(d) Charge transfer electrode structure
(e) Pixel pitches in row and column directions
(f) Interlacing technique, if any
(g) Anti-blooming structures, if any
(h) Active silicon thickness and resistivity
(i) Package window and anti-reflection coatings.

The design features will dictate the choice of operating conditions, e.g. applied potentials, clock rates etc. In practice these may be modified by the effects of manufacturing tolerances.

Quality of Manufacture

Via the effects of variations in all the 'as manufactured' design features, (see CCD device types), both from one CCD to another and across the imaging surface of any one CCD sample, there will be corresponding changes in the MTF. Thus it is important to specify the positions on the CCD at which MTF is to be measured.

Test Conditions

For a given type of CCD, a large number of test conditions must be specified and precisely controlled during any test in order to obtain repeatable MTF measurements.

These conditions include:

(a) Wavelength of the test image irradiance
(b) Numerical aperture of the lens projecting the test image on to the CCD
(c) Maximum and minimum signal levels in the test image and the form of the image pattern
(d) CCD substrate potential, Vss
(e) High and low clock potentials applied to all charge transfer electrodes
(f) Clocking scheme, waveforms etc and clock rates which influence CTI (Charge Transfer Inefficiency)
(g) Interlace, if any, especially when MTF in column direction is to be measured
(h) Temperature of the CCD
(i) Signal processing scheme, including reference level clamping technique
(j) Location(s) of the test image on the surface.

It is advantageous to specify test conditions which represent those imposed by the end user.

[a] On back surface illuminated devices

e2v technologies limited, Waterhouse Lane, Chelmsford, Essex CM1 2QU England Telephone: +44 (0)1245 493493 Facsimile: +44 (0)1245 492492
e-mail: enquiries@e2vtechnologies.com Internet: www.e2vtechnologies.com Holding Company: e2v holdings limited

e2v technologies inc. 4 Westchester Plaza, PO Box 1482, Elmsford, NY10523-1482 USA Telephone: (914) 592-6050 Facsimile: (914) 592-5148
e-mail: enquiries@e2vtechnologies.us

A1A-CCDTN105 Issue 5, June 2003

527/5977

MTF Measurement Procedure

A unique MTF can be defined for an imaging device which responds linearly, uniformly and continuously across its image plane to the incident image irradiance. The MTF is defined theoretically in terms of the device's response to a large area sinusoidally modulated parallel bar pattern, used as an input test image. The value of the MTF at the spatial frequency of the test pattern, is the ratio of the modulation at the corresponding frequency in the device output to the modulation in the input pattern. The modulation itself is also a ratio, namely the amplitude of the sinusoidal irradiance or response variation divided by the mean irradiance or mean response level respectively, see Appendix.

The periodic, pixellated, structure of the CCD sensor surface samples any input image at a fixed spatial frequency. This creates **aliasing** (beat frequency modulation patterns across the sensor output) and destroys the spatial uniformity and continuity of the test images, in particular bar patterns. The apparent MTF derived from such a distorted output varies rapidly with position and a unique MTF cannot be defined.

The local MTF is determined by the phase of the test pattern with respect to the pixel array and is also a function of the angle between the rows or columns of pixels and the bars of the pattern.

However it is possible to specify and declare a detailed measurement procedure that forms an 'operational' definition of a **(pseudo)** MTF, which can be measured with excellent repeatability.

First it should be pointed out that the theoretical measurement of MTF would entail use of a separate test image (chart) for each spatial frequency required. Construction of sinusoidally modulated charts is not easy but use of the readily constructed square wave modulated charts is not worth discussing because they do not overcome the aliasing problem either.

Line Response Function and Computed Static MTFs

The MTF can be derived (Fourier Transform) from the Line Spread Function, LSF, of an optical system. The LSF of an image sensor is meaningless but a Line Response Function, $\mathcal{L}(x)$, can be defined and measured, (see LINE RESPONSE FUNCTION). Then from one measurement of $\mathcal{L}(x)$ any desired form of (pseudo) MTF at any spatial frequency can be calculated. Outline procedures for measurement and calculation of MTF are given in Line Response Function and Line Response Function to MTF (ν) Transformation.

Using the Line Response Function, $\mathcal{L}(x)$, it is possible to calculate the ideal MTF that might be observed as a function of the phase (position) of the ideal parallel bar test pattern, with respect to the pixel array of a CCD. The maximum static MTF[b] is easily calculated for those spatial frequencies where (ν_0/ν) is an integer and $\nu_0 = 1/(2p)$, the Nyquist frequency. Here p is the pixel pitch in a direction perpendicular to the bars of the test pattern.

No useful and unambiguous image structure is available in the CCD output for $\nu > \nu_0$. In fact no useful MTF data is really available in the CCD output for $\nu \geqslant \nu_0/4$. The minimum static MTF[b] may also be calculated and is a fraction of the maximum static MTF which falls rapidly to zero at ν_0.

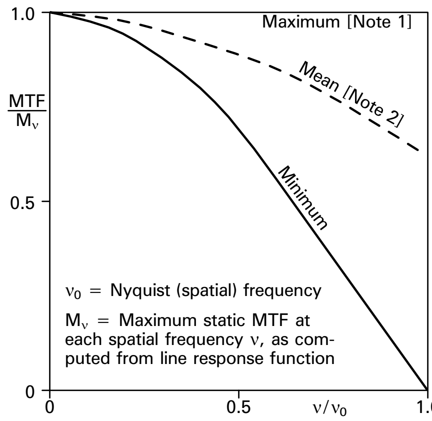
A mean static MTF can be calculated assuming that all phases of pattern are equally likely.

[b] Terminology follows T L Williams, Electro Optical Systems Design Conference Brighton, March 1971

These static MTFs have been referred to as pseudo MTFs because any measurement attempted using the theoretically ideal method would not necessarily yield any of these values. In particular measurement of the minimum value is extremely unreliable.

Since the pseudo MTFs are derived by precisely defined mathematical transformations of the Line Response Function $\mathcal{L}(x)$, any one of them would suffice for specification purposes.

The mean and minimum static MTFs are fractions of the maximum value, which are functions of the parameter (ν/ν_0) alone and independent of the CCD or maximum MTF itself (see Fig. 1). Thus the maximum static MTF forms a useful pseudo MTF which is a function of $\mathcal{L}(x)$, ν and ν_0 alone.



Notes

[1] The results presented were calculated given that the bars of the pattern were parallel to the CCD pixel **columns**. The MTF calculated from the measured line response function at e2v technologies is the maximum value M obtained for the optimum phase of the pattern with respect to the pixel columns.

[2] The mean MTF was calculated with all phases assumed equally probable.

Fig. 1 Spatial variations of static MTF obtained with a sinusoidally modulated bar pattern input test image

Specified MTFs

Aliasing is increasingly important at spatial frequencies exceeding $(\nu_0/2)$. At the Nyquist limit, ν_0, the perceived modulation can vary from zero to a maximum value as the test pattern is shifted by half a pixel pitch across the CCD.

In spite of the fact that real image detail components at the Nyquist spatial frequency limit are subject to extreme aliasing errors, MTF at the Nyquist limit is almost invariably included in CCD performance specifications. It is advisable in these cases also to specify the MTF at other spatial frequencies, e.g. $(\nu_0/4)$.

Fortunately the vernier technique for measuring line response functions, (see Vernier Technique), permits repeatable and accurate estimates to be made of the MAXIMUM static pseudo MTF at ν_0 and at other lower spatial frequencies.

It is important to note that the Line Response Function measuring technique eliminates the effects of veiling glare almost completely.

Veiling glare can degrade the measurements of MTF attempted using parallel bar test patterns.

An objective assessment of veiling glare as it affects a CCD must be the subject of a separate measurement. It will be powerfully influenced by the CCD design and in particular by the window and its anti-reflection coatings or by the use of a fibre-optic coupling plate and by the numerical aperture of the optical system projecting the input image.

LINE RESPONSE FUNCTION

General

The CCD is an almost ideal sensor for capturing the line image profile produced by another optical system, ready for analysis to yield MTF (ν). It provides extremely precise spatial sampling of the image, provided the CCD pixel pitch is sufficiently fine with respect to the width of the line image produced.

When the CCD itself must be characterised it makes no sense to think in terms of line image profiles and the point of view must be inverted so as to consider its line response function.

Line Response Function

The CCD line response function, $\mathcal{L}(x)$ for a single pixel, is defined as the relative response to an infinitesimally narrow irradiated line image situated at a distance x from the centre of the pixel. The line image is aligned parallel to the pixel column if x is measured along the pixel rows or vice versa.

The units chosen for x are mean pixel pitches, p. Thus, actual distances are X = px (mm).

The function $\mathcal{L}(x)$ is normalised for convenience to have unit area under the curve, thus:

$$\int_a^b \mathcal{L}(x).dx = 1 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

Note that (a, b), the lower and upper limits of integration, are chosen to include all non-zero values of the function $\mathcal{L}(x)$ which are distinguishable from the output noise.

Conditions

The CCD sensor and the camera system in which it operates will determine $\mathcal{L}(x)$. Thus, when $\mathcal{L}(x)$ is measured, all the test conditions, including a precise specification of the camera system, must be defined. All conditions ideally should be representative of those to which the system will be subjected in its intended application.

The response of the CCD used to generate $\mathcal{L}(x)$ is the pixel signal defined as total pixel output less the dark current, both integrated over one frame period. In practice, a number of pixel signals will be averaged over many frames in order to reduce the effects of noise. The averaged pixel signals used to derive $\mathcal{L}(x)$ must be linearly related to the pixel input irradiance throughout the range of signals of interest. All signals must be substantially less than the saturation or anti-blooming thresholds and significantly greater than the total noise level.

Sampling the Line Response Function of the CCD

The ideal line response is rectangular with a width equal to the pixel pitch in the direction of interest. A well designed and manufactured CCD will have a line response function with a width at 50% of peak response (FWHM) almost equal to its pixel pitch. However, in practice, the response 'wings' can extend to either side of the origin by one or two pixel pitches. This line broadening will increasingly degrade the MTF (ν) at the higher spatial frequencies.

The precise shape of the line response function and hence the MTF (ν) achieved, is also influenced by the wavelength of the incident light and the mode of operation of the CCD (e.g. depletion depths, etc.) as well as by its design and construction.

If the input test image (illuminated narrow line) is located at a distance x from the centre of the pixel of interest, then the adjacent pixels are located at distances of (x + i). Here i = $\pm$ 1, $\pm$2, etc. (NB x is measured in units of pixel pitches).

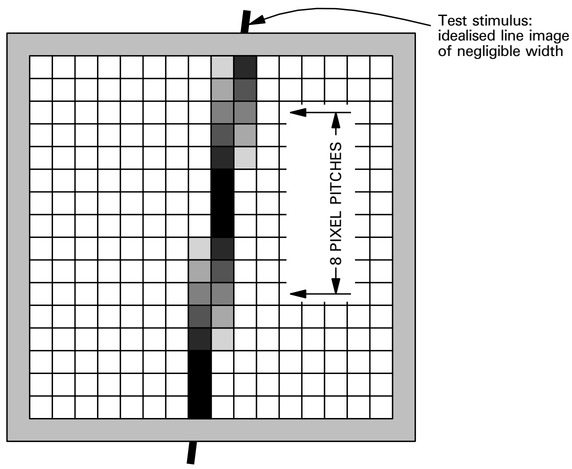
If all pixels in the measurement area of the CCD are assumed to be identical[c], then a row of pixels will provide samples of line response function at intervals of one pixel pitch. Such intervals are too coarse and additional intermediate samples must be obtained to construct a useful response function.

Clearly, mechanically displacing the line image by a small fraction of a pixel pitch (micron movements) between successive frames (exposures) would enable the acquisition of enough response data at intermediate positions to construct a sufficiently accurate response function.

Vernier Technique

An alternative static technique has been devised and is now used for routine MTF (ν) measurements at e2v technologies. This is the VERNIER technique in which the mechanical displacement of the line image has been achieved by tilting the line slightly. Successive pixel rows sample the response function at the pixel pitch but each (row) set of samples is displaced by a fraction of a pixel[d] per row. By interleaving these samples, a sufficiently closely spaced set of samples of the line spread function can be obtained.

The well focused line image is rotated onto approximately the desired angle when it is displaced by one pixel pitch over an interval of say 8 rows, see Fig. 2.



Notes

[1] In this example a 16 x 16 pixel region is designated on the sensor, e.g. enclosed by a one pixel width border suitably highlighted on the image display. The test image is focused as shown with a slope of 1 in 8 with respect to the pixel columns or rows.

[2] An almost ideal sensor will yield a response as illustrated above. The shaded pixels indicate partial responses because the line energy is shared between adjacent pixels.

Fig. 2 Vernier sampling technique to measure the Line Response Function of a CCD

[c] In practice, pixel to pixel response non-uniformities will introduce a fixed pattern noise on the samples.

[d] The currently used fraction is $^1/_8$.

The pixel signals obtained from rows containing the upper and lower column crossing points are shown in Fig. 3. Pixel signals from the central row, on which the line image crosses the centre of a pixel, e.g. at x = 0, are shown in the middle of Fig. 3.

In practice a signal weighted best fit algorithm is employed to compute the slope of the line and its width, which are displayed for the test operator, to focus the line and set its angle.

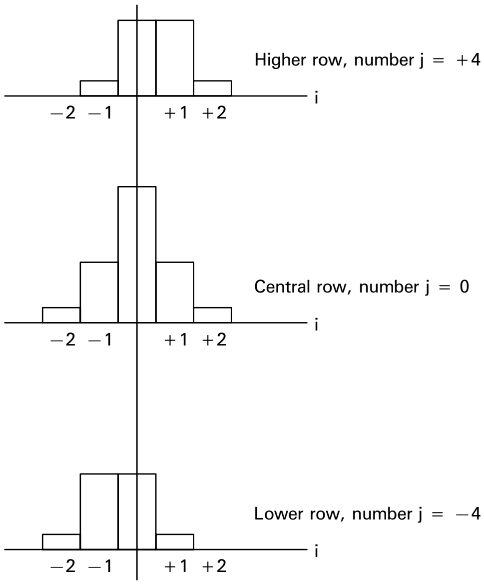


Fig. 3 Pixel signals

LINE RESPONSE FUNCTION TO MTF (ν) TRANSFORMATION

Foundations

It can be shown readily that the modulation transfer function is given by:

$$MTF(\nu) = \sqrt{I_1^2 + I_2^2} \quad . . . . (2)$$

I_1 and I_2 are functions of the spatial frequency, ν, defined by the following integrals of the line response function $\mathcal{L}(x)$:

$$I_1 = \int_{x_1}^{x_2} \mathcal{L}(x) \cos\left[\frac{\pi \nu x}{\nu_0}\right] dx \quad . . . . (3)$$

$$I_2 = \int_{x_1}^{x_2} \mathcal{L}(x) \sin\left[\frac{\pi \nu x}{\nu_0}\right] dx \quad . . . . (4)$$

The limits x_1 and x_2 are set such that all non-zero values of $\mathcal{L}(x)$ are included in the range:

$$x_1 < x < x_2 \quad . . . . (5)$$

The frequency ν_0 is the Nyquist limit for the CCD, which is defined as:

$$\nu_0 = 1/(2p) \ (mm^{-1}) \quad . . . . (6)$$

where p is the pixel pitch in mm.

Symmetrical Line Responses

Note that if $\mathcal{L}(x)$ is an even function symmetrical about x = 0 such that:

$$\mathcal{L}(x) = \mathcal{L}(-x) \quad . . . . (7)$$

then the integral $I_2 = 0$ and

$$MTF(\nu) = I_1 \quad . . . . (8)$$

Generally equation (7) is satisfied and hence equation (8) is applicable to many CCDs.

If operating conditions significantly degrade the Charge Transfer Efficiency then the symmetrical form of the CCD line response will be distorted and equation (8) would not apply. It is standard practice at e2v technologies always to calculate I_1 and I_2 and to use equation (2).

APPENDIX

Modulation

The contrast between two specified areas of an image with irradiances E_1 and E_2, is defined here[e] by the ratio

$$\frac{(E_1 - E_2)}{(E_1 + E_2)}$$

The Modulation Transfer Function, MTF, describes the response of an optical device or system to an ideal input test image comprising a pattern of alternate parallel light and dark bars with a sinusoidal variation of irradiance scanned in a direction perpendicular to the pattern bars.

The irradiance in this ideal test image is represented by a continuous function of the form

$$E(\nu, X) = e_0 + e(\nu)\cos(2\pi\nu X) \quad \text{(i)}$$

Where:

$E(\nu, X)$ = Image irradiance
ν = Spatial frequency of the pattern (cycles/mm)
X = Distance across the bars (mm)
e_0 = Amplitude of the zero frequency component, i.e. mean irradiance
$e(\nu)$ = Amplitude of the irradiance variation at frequency ν.

The modulation in such a pattern is the contrast (definition above) between the areas of maximum and minimum irradiance in adjacent light and dark bars of the pattern. Clearly these irradiances are $E_1 = e_0 + e(\nu)$ and $E_2 = e_0 - e(\nu)$, hence the modulation $M_i(\nu)$ is given by the ratio

$$M_i(\nu) = \left[\frac{e(\nu)}{e_0}\right] \quad \text{(ii)}$$

If the device or system responds linearly and uniformly[f] to the input image irradiance within a specified area of the image, then here the output response may also be described by a continuous function

$$R(\nu^1, X^1) = r_0 + r(\nu^1)\cos(2\pi\nu^1 X^1 + \beta) \quad \text{(iii)}$$

Where

ν^1 = Spatial frequency at output corresponding to ν at the input (as modified by the image magnification)

X^1 = Distance across the bars of the output image (mm)
β = Phase of the output pattern at frequency ν^1 and at the origin chosen for X^1.

The modulation in this output response is

$$M_o(\nu^1) = \frac{r(\nu^1)}{r_0} \quad \text{(iv)}$$

The efficiency with which input modulation of the ideal test image is transferred to the output is described by the ratio

$$MTF(\nu) = \frac{M_o(\nu^1)}{M_i(\nu)}$$

Clearly at $\nu = 0$ the input and output modulations are unity by definition and hence the MTF at $\nu = 0$ is also unity.

In real devices or systems with finite image fields, it is impossible to examine the response at zero spatial frequency. Arbitrary choices must be made and the MTF is normalised to unity at the lowest convenient spatial frequency. This can introduce significant differences between various measurement techniques, caused by the effects of veiling glare.

In a television system the coupling of video signals representing various spatial frequencies in the image is AC. The zero or low frequency mean level is not DC coupled and is determined by clamping the dark signal to some arbitrary level, which directly affects the modulation measured. The MTF of an electro-optic image sensing device, e.g. a CCD, can only be determined if the electronic offsets are removed and a clearly defined dark level is established within the area of the image tested.

[e] In other contexts different contrast definitions may be employed.
[f] That is with spatially uniform transmission or gain.