COMPARISON OF MODULATION TRANSFER FUNCTION MEASUREMENTS FOR ASSESSING THE PERFORMANCE OF IMAGING SYSTEMS.

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Abstract - **Modulation Transfer Function (MTF) is the basic tool widely used in assessing the performance of imaging systems. The most common imaging systems employed in MTF measurement include image capture devices and medical imaging systems. The various methods of MTF used in assessing the performance of these imaging systems have shown different outcomes. It is still not clear the exact method that should be adopted as a standard procedure in the measurement of MTF. In this review, we summarize, compare and identify research gaps on some works that have been done toward measurement of MTF. Cataloging these varieties of methods and outcomes may help simplify future investigations of MTF measurement as well as identify a standard procedure which should be followed in the measurement of MTF for imaging systems.**

Key words - Modulation Transfer Function, Nyquist frequency, Spatial frequency, Fourier transform.

I. INTRODUCTION

The Modulation Transfer Function (MTF) is a method commonly used to quantify the performance of most imaging systems. Images from capture devices such as camera-based systems, flat-bed scanners, drum scanner and medical imaging systems such as Computed Tomography (CT) scanners are commonly employed in MTF measurement. The performance of an imaging system is characterized by spatial resolution. Spatial resolution is how well an imaging system can differentiate small objects that are adjacent to one another. MTF is a common metric used in defining the spatial resolution characteristics of imaging systems [1].

The MTF of an imaging system can be measured directly or indirectly. Indirect measurement of MTF is obtained from either the spread function or the edge response function. Measurements taken from images of photographic emulsions are often degraded by noise and the data obtained from physical experiments contains errors. As a result, current measurement of MTFs either directly or indirectly requires some degree of smoothing to minimize these errors.

In the spatial domain, the spatial resolution of an imaging system is characterized by its point spread function (PSF). Theoretically, the PSF is the image of an infinitesimal point object that can be defined as a function in two-dimension. The MTF is then obtained from the PSF as the magnitude of its two-dimensional Fourier transform. In practice, one major limitation in determining the PSF is the difficulty to produce exactly the image of the infinitesimal point object. In order to reduce the difficulty associated with measuring the PSF, a slit was introduced to measure the Line Spread Function (LSF). The LSF is a one-dimensional representation of the two-dimensional PSF. The width of the slit must be sufficiently narrow so that the spread in the image slit does not entirely contribute to the blurring. The Fourier transform of the LSF is the MTF. Alternatively, measuring the MTF using the edge approach requires an object that transmits radiation on one side of an edge, but is perfectly attenuating on the other. The density profile from the image of the edge gives the Edge Spread Function (ESF). The derivative of the ESF is the LSF, the Fourier transform of which yields the MTF in one dimension [2].

Several methods have been proposed from previous works for measuring the MTF of optical systems based on detector arrays of charge-coupled devices. These methods differ mainly in the type of target or pattern used as object pattern [3]. These techniques have been classified into five categories; the sine-wave method, the bar-target method, the edge-gradient method, the series-expansion method and the random pattern method [4].

In this review, we have summarized, compared and identified some limitations of some previous works that have been done toward the measurement of MTF.

II. THE MEASUREMENT OF MODULATION TRANSFER FUNCTION WITH DIFFERENT TARGETS

Measurement of MTF from PSF in computed tomography is often performed by scanning a point source phantom such as a thin wire or a microbead. These methods are most widely utilized in current CT systems [5-12] as they are conceptual simplicity and relatively easy to implement. The method used in determining the PSF using the bead and the thin wire are described in the Catphan 600 phantom laboratory manual [13] and Kayugawa et al.[14] respectively. As indicated by Kayugawa et al., it is difficult to exactly determine PSF and MTF with high precision and accuracy because the image of the point source is blurred and degraded noise by the imaging system. There is a dependence of PSF on the region of interest (ROI) in the image of the point source. As a result, the MTF is largely affected by changing the ROI. Increasing the ROI in general tend to increase the MTF. However, this trend is not consistent as the MTF values produced can show random variation with some kennels as the ROI increases.

Measurements of PSF can be limited by the Nyquist frequency of the discretization in the acquisition system. In order to overcome this, the image of a knife or step edge is required. However, the image produced is usually a blurred step image and several ESFs have to be estimated along the length of the edge in order to reduce the blurredness. Each of the ESFs are then registered to a reference point (Fig. 1) and accumulated to form a super-resolution ESF that contain frequency information above the Nyquist limit of the sampling grid.

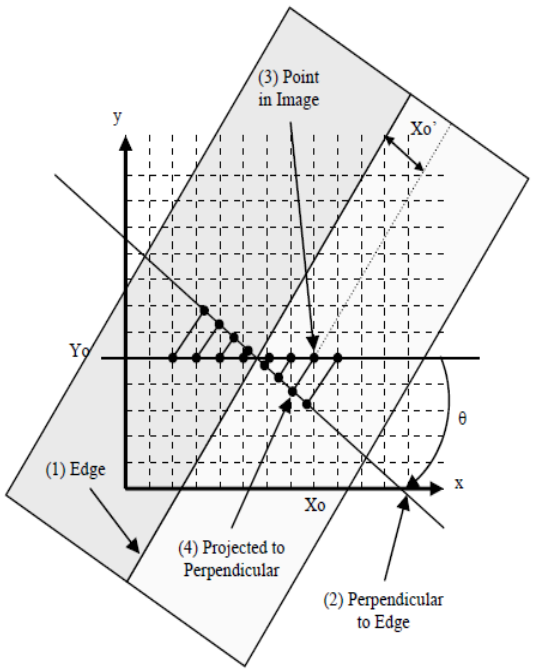

Figure 1: ESF registration onto a reference point

The PSF is more useful than the ESF for DFD measurement and image simulation as it can be directly convolved with an input image to estimate the output image [15,16,17]. In practice PSF information beyond the Nyquist limit of the array is often required, Reichenbach *et al* [18]. The PSF is obtained by differentiating the ESF. One difficulty in using a step edge image to estimate the PSF is that, any level of low noise in the ESF can result in high levels of noise in the PSF and render it unusable. The Fourier transform of the PSF is the Modulation Transfer Function (MTF), and both measures have been widely used to characterize the performance of imaging systems.

The most frequent way in determining the MTF using the edge method is by obtaining the ESF from the image of an opaque surface and differentiating the ESF to obtain the LSF. The differentiation has been done in different ways, each with its outcome[19-21]. For example, the differentiation has produced a non symmetric LSF curve with negative values. As result, the MTF values are significantly affected such that only values of MTF below 0.15 are shown to illustrate detail at high spatial frequencies [19-21]. Alternatively, some researchers have differentiated the ESF numerically without forcing their data to an assume model using the finite element technique. This technique has shown that, the resulting MTF (taking the Fourier Transform of the LSF) contains an error due to the spacing of the sampled data if the system is not sufficiently oversampled [22]. As a result, detail of MTF values would be under estimated or over estimated for sampling rates less than four times (x4) or greater than four times (x4) the Nyquist frequency.

Also, an alternative method under the edge method for measuring the MTF is the slanted edge method. This method which is well established in ISO 12233 [23] still presents some disadvantages, the most principal one being the long measurement time. The slanted edge method requires imaging an edge onto a detector, slightly tilted to the detector rows (or columns). Orienting the edge vertically produce a horizontal spatial frequency detector responds which gives different ESF due to different phases. This causes the ESF to be under sampled and therefore affects the MTF. Although it possible to increase the sampling frequency mathematically by projecting the data along the edge [24], ideally the orientation of the edge to the detector should produce an ESF above the Nyquist frequency.

The MTF of an imaging system has also been measured with a bar target. This approach is achieved by taking the image of a fabricated three-bar or four-bar binary pattern with equal width of lines and spaces. Each bar target is specified in terms of its fundamental frequency. The modulation depth of the image waveform is then measured as a function the fundamental frequency. This measurement has proven to introduce extra frequency components at both higher and lower frequencies than the fundamental frequency [25]. These frequency components can be removed by computation using the Fourier decomposition of the square waves [26]. However, the Fourier decomposition of the square waves are not strictly valid because the Fourier transform of the three-bar and four-bar target is a continuous function of frequency rather than discrete harmonic Fourier series.

Another approach which is used in the measurement of MTF is the sine-wave method. This method requires an exposed photographic emulsion with varying sinusoidal intensity distribution of known spatial frequency and modulation. The image of the sinusoidal emulsion is then scanned with a microdensitometer to give the effective exposure modulation. The MTF is then calculated as the ratio of the output effective exposure modulation, to the input exposure modulation at a given spatial frequency (Fig. 2).

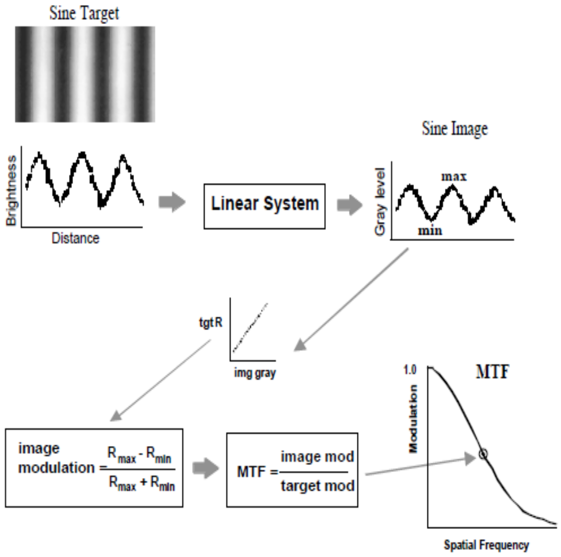

Figure 2: Generating the MTF curve from a sine wave target.

One major difficulty with this method is the production of targets with accuracy that are truly sinusoidal with known modulations [27]. This results in relatively low signal strength at high spatial frequency and poor overall optical efficiency.

III. Conclusion

MTF is the most widely acceptable way of verifying the performance of most imaging systems in terms of their spatial resolution and contrast. However, previous studies on MTF have shown that MTF can be ambiguous when used to characterize errors that can cause the MTF to deviate from its expected value. This variation in errors is due to the type of target or pattern used as object pattern. Hence for coherence MTF results on future research works, we proposed from this review a unique type of target or wave pattern specific to every imaging system as test objects. This would help produce consistent MTF results devoid of the method used as well as reduce the ambiguity towards the measurement of MTF. In addition, working equations should be developed for specific targets for future image evaluation methods to serve as correction factors for MTF measurement. The various techniques analyzed in this paper can help provide useful guidelines and expected outcomes for future research works in MTF measurement.

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