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Original paper

Chirp phantom for MTF calculations. A study of its precision in noisy environments

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A R T I C L E I N F O

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A B S T R A C T

Bar pattern phantoms are used to determine the maximum number of line-pairs per mm that an imaging system can resolve. In some cases, a numerical determination of the modulation transfer function (MTF) can also be carried out. However, calculations can only be performed in a relatively small number of frequencies because of the small number of bar groups in the phantom. In this work, a new bar pattern phantom has been simulated. This phantom consists of 66 pairs of lines of different periods and these periods vary exponentially with spatial position, like in a chirp wave. An oversampling procedure has been implemented to obtain the pre-sampled MTF of the system and the results obtained have been compared with those obtained with the edge method, recommended by the IEC. Monte Carlo simulations were carried out for three different levels of noise aimed at investigating the effect of noise on the uncertainties of the MTF determination. In addition, using the analytic expressions for the MTF calculation, statistical fluctuations of noise in phantom images were propagated to MTF values. Despite the smaller size of the chirp phantom, uncertainties in the chirp method are smaller than those of the edge method. For the edge image, the standard deviation of the MTF is proportional to the frequency f, whereas for the chirp method it is proportional to its square root. It is shown that applying an oversampling method allows the use of a single line pair per period without compromising the precision in noisy environments.

1. Introduction

The modulation transfer function (MTF) of an imaging system characterizes the frequency response of the system, describing its signal transfer characteristics as a function of spatial frequency.

Test objects like pin-holes [1], slits [2], wires [3,4], linear bar patterns [5,6], and edges [7–15] have been used to calculate the MTF.

In discrete imaging systems the detector response to a signal may depend on the imaging properties of the detector and on the location of the signal pattern relative to the sampling grid of the detector [16]. Also, if the image is not sampled finely enough to record all spatial frequencies aliasing will be present.

To overcome these issues oversampling procedures have been developed [2,6,8,10,17]. Oversampling minimizes aliasing by obtaining a presampled MTF and increases signal to noise ratio (SNR), allowing the MTF determination in noisy environments.

The standard IEC 62220-1 describes a procedure for determining the MTF of radiology equipment [12]. This standard specifies beam qualities, test phantoms, and image processing techniques required for the MTF calculation. The recommended test phantom is a radio-opaque edge, and the processing of the test object image includes an oversampling procedure to obtain a pre-sampled MTF.

Recently, oversampling procedures have been applied to periodic test objects like star bar patterns and linear bar patterns [6,17]. It has been shown that these procedures remain accurate even in the presence of high levels of noise. In such situations, periodic patterns outperform the edge method in terms of immunity to noise.

Bar pattern phantoms are often used to study the spatial resolution of imaging systems in radiology. These phantoms have several line-pair groups at different resolutions, each group containing several pairs of lines. After imaging the phantom, a visual inspection determines the highest resolution group that can be seen. In addition to this widespread use, methods to calculate the MTF of imaging detectors in digital radiology [6] and CT [5] have been developed.

Using a star bar pattern phantom or an edge phantom allows the calculation of the MTF at any value in an interval of frequencies [8,17]. On the other hand, the calculation of the MTF from a bar pattern phantom is limited to the frequencies of the bar groups that it contains, and this is usually a small number of frequencies. To overcome this issue, a new phantom is studied in this work. The purpose of this phantom is twofold: to allow the calculation of the MTF in a large number of frequency values and to provide a high immunity to noise.

The phantom is composed of 66 contiguous pairs of bars with exponentially decreasing periods, and the images of the phantom are

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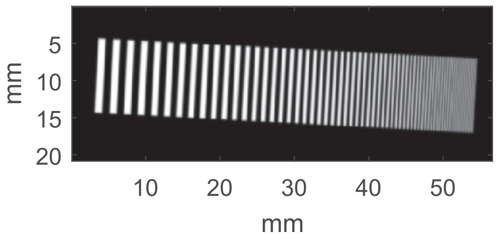
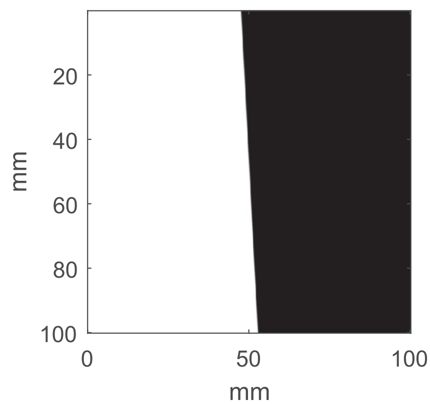


(a) Chirp phantom image.



(b) Edge phantom image.

Fig. 1. Synthetic phantom images used for MTF calculations.

generated through a process that simulates blurring, sampling and noise addition. Phantom images generated in this work emulate those found in radio-diagnostics regarding phantom characteristics, noise levels, spatial resolution and smoothness.

In order to investigate the influence of noise on the uncertainties of the MTF calculations, Monte Carlo simulations were carried out. Also, the results obtained were compared to those obtained by the edge method, proposed by the IEC. Finally, analytical expressions for the SNR of the calculated MTF's were derived.

2. Materials and methods

2.1. Phantom images

The chirp pattern has a size of 10.0 mm × 51.0 mm. Each of its 66 pairs of bars has a height of 10.0 mm and a period ranging between 2.0 and 0.2 mm spanning a frequency range of 0.5–5 mm^{-1} (see Fig. 1a). On the other hand, the edge phantom has the shape and dimensions recommended by the standard IEC 62220-1 (Fig. 1(b)). Images were created following four steps.

- First a delta-sampled image of each phantom is created with a resolution of 10 μ m× 10 μm. The images created at this step are binary, using 0 as the low value and 1 as the high value.
- In a second step, the phantom images are low-pass filtered by convolving them with a rotationally symmetric exponential point spread function (PSF), $g(x,y) = K^* e^{(-r/\sigma)}$, where $r = \sqrt{x^2+y^2}$,$\sigma = 70$ μm and K is a normalization constant.
- After convolution, the pattern images are downsampled to a resolution of 140 μ m× 140 μm. Fig. 1 shows the images at this step.
- Finally, white Gaussian noise is added to obtain the final simulated phantom image.

The amount of noise was measured in dB of peak signal to noise ratio (PSNR), defined as the ratio between the maximum possible power of the image and the power of corrupting noise, $PSNR(dB) = 10\log_{10}\frac{I_0^2}{\sigma_n^2}$, where σ_n is the noise standard deviation and, in this case, $I_0 = 1$. In an ideal detector, the square of the signal to noise ratio q ($\text{mm}^{-2}nGy^{-1}$) relates to PSNR by $PSNR(dB) = 10log_{10}(qD\Delta^2)$, where D is the absorbed dose in nGy,Δ is the pixel lateral size in mm and q is the beam quality, as defined by the IEC [12].

Table 1
Relationship between noise level (in dB of PSNR) in an ideal detector and detector dose D.

Noise	20 dB	40 dB	60 dB
D	0.174 μGy	17.4 μGy	1.74 mGy

For instance, using the radiation quality RQA5, defined by the IEC [12], and a pixel size of 140 μ m× 140 μm, the relationship between dose in an ideal detector and noise level is shown in Table 1.

2.2. MTF calculations

2.2.1. Chirp phantom

In order to obtain the MTF, the area where the bars appear in the image is used to obtain an oversampled profile. Then, the MTF is obtained from the Fourier series of this profile.

Every pixel of this area was classified with respect to a straight line parallel to the bars. The criterion followed for classification was the distance from the centre of the pixel to that line. The set of possible distances was discretized into bins of a size equal to 1/10 of the pixel size and the value of each pixel was assigned to the corresponding bin.

All the pixel values in each bin were averaged and the resulting mean was assigned to the distance from the centre of the container to the reference straight line, in this way a new profile was created (see Fig. 2). In this figure, the profile is calculated on the image resulting from adding noise of 40 dB of PSNR to the image in Fig. 1(a).

This procedure results in an oversampling ratio of 10; the sampling frequency of the created profile is ten times larger than that of the image. It is worth noting the good SNR that can be seen in the profile in Fig. 2. This good SNR is because every pixel in the analysis area of the image in Fig. 1(a) is used to obtain the profile: The information in a 2D image has been condensed into a 1D profile.

The discrete profile in Fig. 2 is composed of consecutive cycles, varying in amplitude and frequency. Each of these cycles correspond to one pair of bars in the chirp phantom image, and can be seen as a periodic wave: the discrete output wave of the system for a continuous square wave input $s(x)$ with the same frequency.

Given a presampled output wave $o(x)$ of frequency f, the system MTF at this frequency can be calculated as the ratio

$$MTF(f) = \left|\frac{O_1}{S_1}\right|, \tag{1}$$

where O_1 is the 1^{st} Fourier series coefficient of the output wave and S_1 is the 1^{st} Fourier series coefficient of the square wave input.

For a square wave $s(x)$ of amplitude A, the Fourier coefficients (for odd l) satisfy $|S_l| = \frac{2A}{l\pi}$, being zero for even l. Thus, the MTF at frequency f can be calculated as

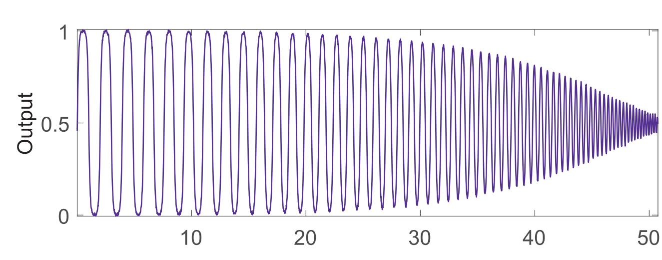


Fig. 2. Profile obtained after oversampling the image resulting of adding noise of 40 dB of PSNR to the image in Fig. 1(a).