Image Evaluation and Analysis of Ink Jet Printing System (I) MTF Measurement and Analysis of Ink Jet Images

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Abstract

In this study, MTFs of papers which included both mechanical and optical dot gain were measured from samples printed by an ink jet printer on glossy coated, matte-coated and uncoated papers, MTFs were measured from sinusoidal patterns and Fourier transform of line spread function from one-pixel line and step image. Those obtained MTFs were analyzed and compared in both horizontal and vertical printing direction. In addition, MTF of paper related to optical dot gain were also measured by contacting sinusoidal pattern on papers. The MTF of print and MTF of paper showed nonlinear relationship. Finally reflection densities were predicted by MTF of print measured from printed step image and it was found that reflection density is not well predicted when comparing to the reflection density measured by a conventional densiometer.

Introduction

At present ink jet printer has been widely used in desktop publishing since its low cost and acceptable image quality. However its image quality hardly match the quality of photographic system. The main reason is printing image has to be halftone image. The halftone dots when printed on paper will cause an important phenomenon called dot gain. This significantly influences to sharpness, tone and color reproduction of printed image. To achieve good image quality dot gain phenomenon must be compensated in the process of transformation to halftone image before sending data to the printer.

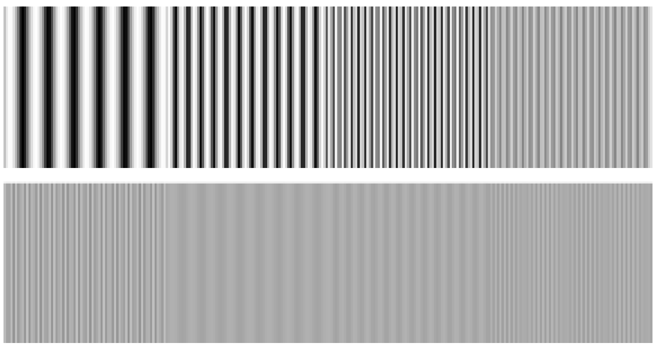
It is well known that there are two types of dot gain, mechanical and optical dot gain, caused by lateral spread of ink on paper and lateral scattering of light in paper respectively. Yule and Nielsen[1] firstly introduced n factor accounting for optical dot gain. The n factor depend on halftone frequency and light scattering properties of paper. Arney[2] et al expanded Murray-Davies model and separately modeled mechanical and optical dot gain effect. Since these are empirical models and cannot be determined theoretically. Some theoretically models have been studied[3-5]. These models can be used to predict the reflectance or reflection density of a halftone image by knowing some certain measurement values for example reflectance of bulk paper and solid area and point spread function of paper. Point spread function of paper (PSF) can be expressed by another practical metric in frequency domain, the MTF. MTF of paper (MTF_p) can be measured by several techniques, however the spread of ink on paper has not actually been measured. Since printed halftone image is always included light scattering in paper, it is very difficult to separately measuring these two dot gain. In fact MTF of image cause by ink spread (MTF_i) is small when compare to MTF_p and it can be ignored in several printing systems. Therefore MTF of paper can be represented for both types of dot gain. However since some printing systems use water based ink, also some types of ink jet printers, they trends to have more mechanical dot gain unless using specific type of substrate or paper. Our ultimate goal is to establish sharpness device independent system thus it is a challenging topic to find MTF_i. Like color management system we also need to know every device characteristic concerning sharpness of the system. MTF_i will play an importantant role in the case of simulation the sharpness of out put on monitor with the same paper (the same optical dot gain) but different printer.

If we assume that MTF_i and MTF_p have linear relationship, the MTF of print (MTF_{pr}) will equal to multiplication of both MTFs as in Eq.(1)

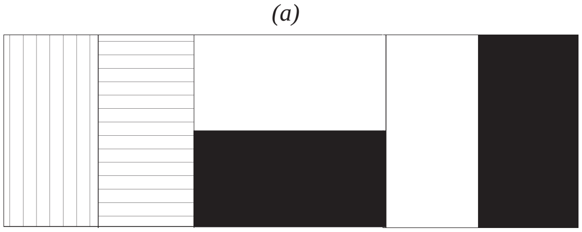
$$MTF_{pr} = MTF_i \times MTF_p \qquad (1)$$

Measuring MTF of Print

We measured MTF_{pr} from ink jet images by two techniques. The first was measuring the degree of modulation reduction from printed sinusoidal pattern and the second was the Fourier transform of line spread function measuring from one-pixel-line image and step image. The images shown in Fig.1 were created by Matlab at sampling rate 720 ppi.



(a)



(b) *(c)*

Figure 1. Experimental images (a) sinusoidal pattern (b) one-pixel line image and (c) step image

The sinusoidal pattern consists of eight different frequency patches, 0.25, 0.50, 1, 2, 4, 6, 8 and 10 cycles/mm respectively. It was transformed to halftone image before sending to the printer by two algorithm, Bayer and Error Diffusion. These halftone images together with one-pixel line and step image were printed by Epson PM770C at 720x720 dpi on glossy coated, matte-coated and uncoated paper. Printed images were measured by a microdensitometer (Konica PDM-5) with aperture 1000x25 µm and 5 µm interval. The scanned densities *D(x)* from sinusoidal patterns, one-pixel lines and step images were transformed to reflection intensity *I(x)* by the following formula

$$I(x) = 10^{-D(x)} \tag{2}$$

Sinusoidal Method

MTFs from sinusoidal method were calculated by Eq. (3) and (4).

$$MTF(\omega) = M(\omega) / M'(\omega) \tag{3}$$

$$M(\omega) = \frac{I_{\max}(\omega) - I_{\min}(\omega)}{I_{\max}(\omega) + I_{\min}(\omega)} \tag{4}$$

where $M(\omega)$ denotes the modulation of the printed sinusoidal image at ω frequency and $M'(\omega)$ denotes the modulation of digital sinusoidal pattern which equal to 1. $I_{\max}(\omega)$ and $I_{\min}(\omega)$ are the average maximum and minimum intensity. Fig. 2 shows the scanning intensity at some spatial frequencies from Error Diffusion halftone image printed on glossy coated paper.

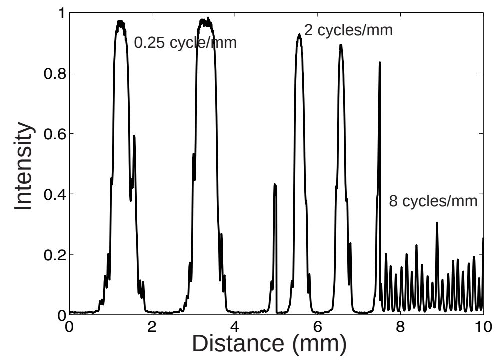


Figure 2. Intensity trace from sinusoidal image at spatial frequency 0.50, 2 , and 8 cycles/mm printed on glossy coated paper.

One-Pixel Line Method

MTFs of one pixel line images were calculated by Eq. (5)

$$MTF = \left| \int LSF_l(x) e^{-j2\pi\omega x} dx \right| \tag{5}$$

$LSF_l(x)$ denotes the line spread function obtained by

$$LSF_l(x) = 1.0 - I_l(x) \tag{6}$$

where $I_l(x)$ is the reflection intensity of one-pixel line image. Figure 3 shows the line spread function of one-pixel image on three types of paper.

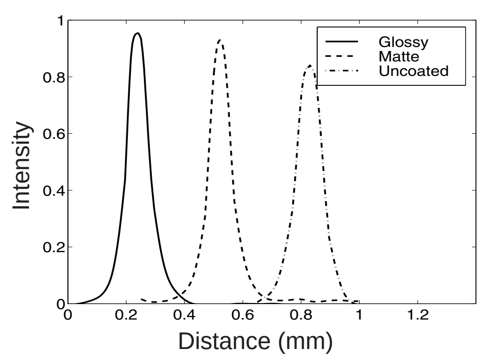


Figure 3. Line spread function from one-pixel line images printed on glossy coated paper.

Step Image Method

MTFs of step images were calculated by Eq. (8) and (7).

$$MTF = \left| \int LSF_s(x) e^{-j2\pi\omega x} dx \right| \tag{7}$$

LSFs(x) denotes the line spread function of the following formula:

$$LSF_s(x) = \frac{d(s(x))}{d(x)} \tag{8}$$

where *s(x)* is the reflection intensity of the edge trace from step image. Fig. 4 shows the line spread function of three types of paper.

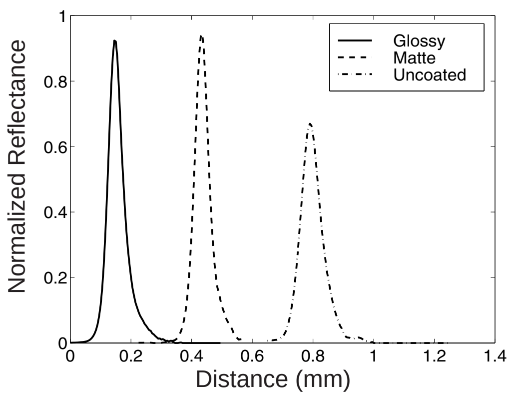


Figure 4. Line spread function from step images printed on glossy coated paper.

MTF Measurement Method Comparison

The MTF of print measuring from these three methods were corrected by system MTF. As we consider in spatial frequency less than 10 cycles/mm, the MTF of microdensitometer itself is unity however correction must be made for the scanning width. We calculated the MTF of system by first convoluting step function with aperture width and then applied with Eq. (8) and (7). The MTF at 10 cycles/mm is about 90%.

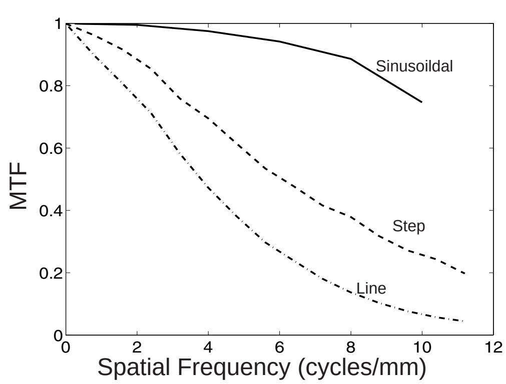


Figure 5. MTF from sinusoidal, one-pixel line and step image printed on glossy coated paper.

We can observe from Fig. 5 that MTF from sinusoidal method is higher than the others. Since this method has aliasing effect and bilevel characteristic trends to give high modulation than it should be, it is not appropriate to measure MTF of print. The measurement of one-pixel line and step image are easier and have no aliasing effect. Between these two methods, one-pixel line method has lower MTF because of line width. If the line is delta fuction MTF from one-pixel image will be the same as MTF from step image. This can be simulated by convolution step function and rectangular function at different width with the same PSF and then convolute again with aperture width. The line spread function can be obtained from the result of convolution. When apply Fourier transform, this will result in MTF. From these results we selected the step image method to analyze the MTF of different types of paper.

MTF of Different Type of Paper

When we compare MTF of print from vertical edge images shown in Fig. 6, uncoated paper shows lowest while MTF of glossy coated slightly lower than mattte-coated paper. Because the glossy coated paper used in the experiment is thicker than matte coated paper this might be the reason for this difference.

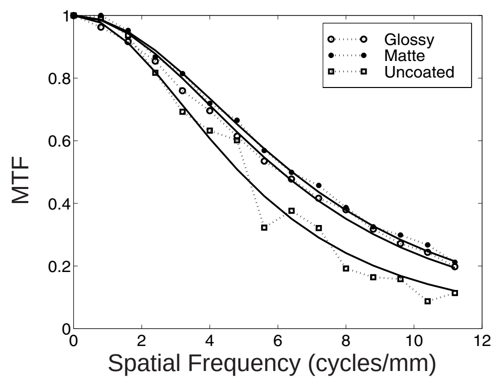


Figure 6. MTF from step images printed on glossy coated, matte-coated and uncoated paper. The solid lines are MTFs calculated from model in Eq. (9) with d=0.020, 0.19 and d= 0.025 for glossy, matte and uncoated paper respectively.

To fit the experimental data with a model, we adopted empirical MTF model[6] as shown in Eq. (6)

$$MTF(\omega) = \frac{1}{\left[1 + (2\pi d\omega)^2\right]^{3/2}} \tag{9}$$

The *d* value can be thought as coefficient accout for ink spread and light scattering in the paper. The *d* vaules, 0.020, 0.019 and 0.025 were selected to best fit with experimental data by minimize RMS deviation for glossy, matte and uncoated paper respectively and the fitting curves are shown as solid line in Fig. 6.

MTF of Different Printing Direction

The result in Fig. 7 shows very similar MTF measuring from glossy coated paper in vertical and horizontal printing direction. If we assume that glossy coated paper is isotropic, we can conclude that there is very little MTF difference from different printing direction.

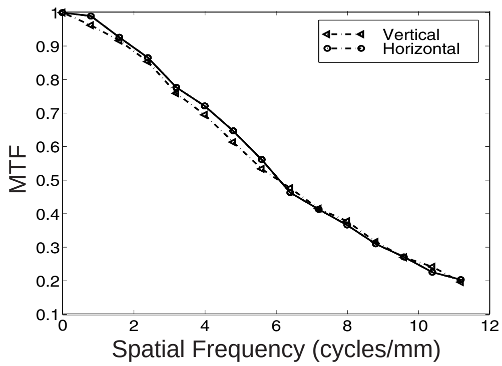


Figure 7. MTF from step images printed on glossy coated paper in vetical and horizontal printing direction.

Measuring MTF of Paper

We used contact sinusoidal pattern technique[7] to measure contrast transfer function (CTF) of paper. The calculation from CTF to MTF was carried out by combining Eq. (10), (11) and (12).

$$MTF(\omega) = 2 \cdot CTF(\omega) - 1 \tag{10}$$

$$CTF(\omega) = \frac{C(\omega)}{C(0)} \tag{11}$$

$$C(\omega) = I_{max}(\omega) - I_{min}(\omega) \tag{12}$$

The contrast *C(ω)* is the different of maximum and minimum of intensity at ω frequency which can be obtained from using microdensitometer scans the contact sinusoidal film on paper. The scanned densities were tranformed to intensity by Eq.(2) . We used scanning aperture at 1000x25 μm with 5 μm interval. The measurement CTFs were corrected by system MTF. The MTFs of paper from glossy coated, matte-coated and uncoated paper are shown in Fig.8. The solid lines are calculated from the Eq. (9) with *d* value 0.052, 0.025 and 0.035 respectively.

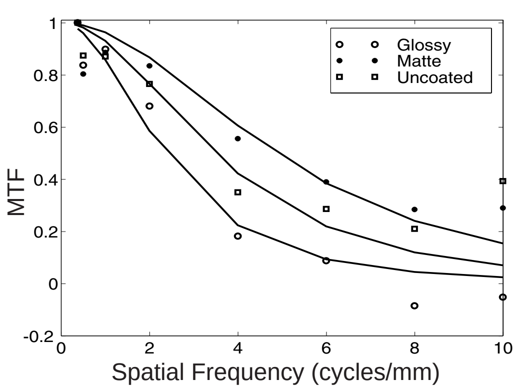


Figure 8. MTFs from contact sinusoidal pattern film on glossy, matte and uncoated paper. The solid lines are MTFs calculated by the model with d values 0.052, 0.025 and 0.035 respectively.

Discussion

If we assume that MTF_i is 1.0 the mesurement MTF_{pr} is merely dependign on MTF_p or light scattering property of paper. When multiplying with MTF from ink spread on paper, the MTF_{pr} should be lower than MTF_p. Our measuring MTF_p shows that MTF_p of glossy paper is the lowest. However its MTF_{pr} is higher than the MTF of uncoated paper. If we use Eq. (1) to solve the MTF_i the result will greater than 1 when spatial frequency increase which is not possible. Therefore the relationship of MTF_i, MTF_p and MTF_{pr} is not linear and rather complex. One reason of this phenomenon is that ink dot does not only spread but also penetrate into paper. When ink penetrates into the paper, the distance of paper between ink and background will decrease. With thin paper and black background most of the light will be absorbed rather scatter. Therefore the thinner of paper or the deeper penetrate of ink into the paper the less light scattering or high MTF will be observed. To model this behavior successfully the microstructure of ink penetrate into the paper must be well understood.

Prediction of Reflection Density

Since MTF_{pr} included both mechanical and optical dot gain, it is possible to be used to predict the reflection density of halftone image. We used Eq.(13) for calculate the reflection density *Dr(x,y)* of ink jet halftone tints.

$$Dr(x,y) = -\log\{[T(x,y) * Rpsf(x,y)]T(x,y)\} - \log(Rr), \tag{13}$$

where *Rr* denotes reflectance of bulk paper; *T(x,y)* is the transmittance of halftone image array; *Rpsf(x,y)* is the normalized PSF obtained by Eq.(14) and its 3D graph is plotted in Fig. 9.

$$Rpsf(x,y) = \frac{1}{2\pi d^2} e^{\frac{-\sqrt{x^2+y^2}}{d}} \tag{14}$$

Line screen pattern with screen frequency 45 and 180 lpi were printed on matte-coated and uncoated paper. Sakura densitometer (PDA-65) was used to measure reflection density. Every original halftone pixel which has value equal to zero (to be printed as ink dot) is replaced by transmittance of ink layer obtained by square root of reflectance from solid area. The white pixel (value 1) is the normalize paper base. This is *T(x,y)* in Eq.(13) and was convoluted by *Rpsf*. The results from convolution were multiply by image array again. When apply logarithm to the mean reflectance from image array we will get reflection density. Fig. 10-13 show the comparison of measured density with predicted density and density calculated from reflectance obtained by Murray-Davies equation.

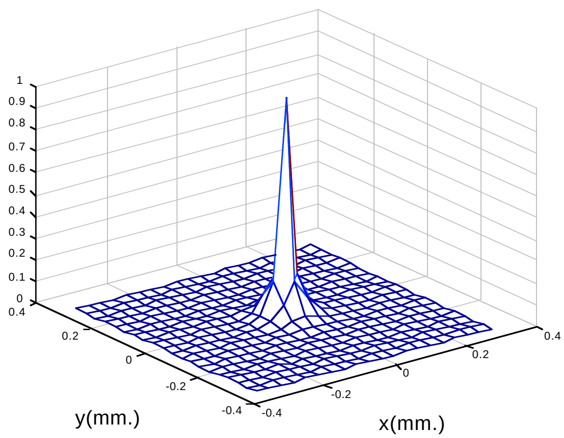


Figure 9. Normalized Rpsf with d=0.019

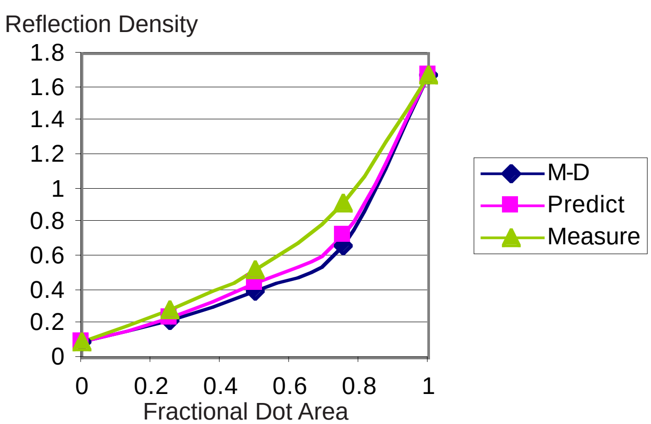


Figure 10. Reflection density of line screen 45 lpi printed on matte-coated paper.

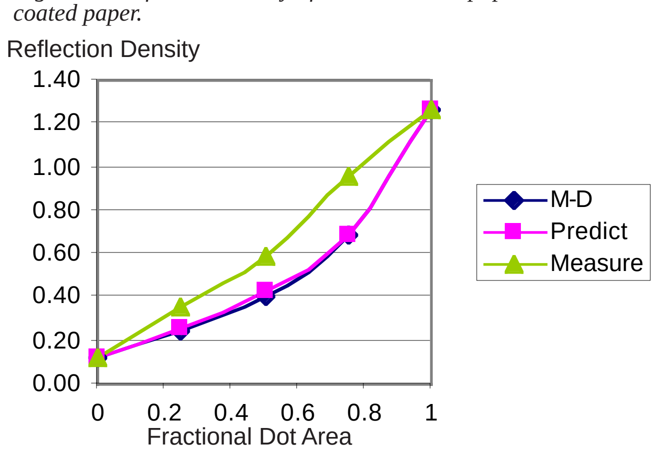


Figure 11. Reflection density of line screen 45 lpi printed on uncoated paper.

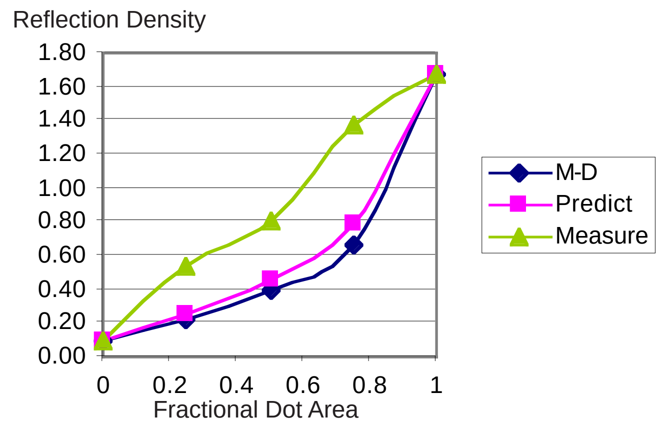


Figure 12. Reflection density of line screen 180 lpi printed on matte-coated paper.

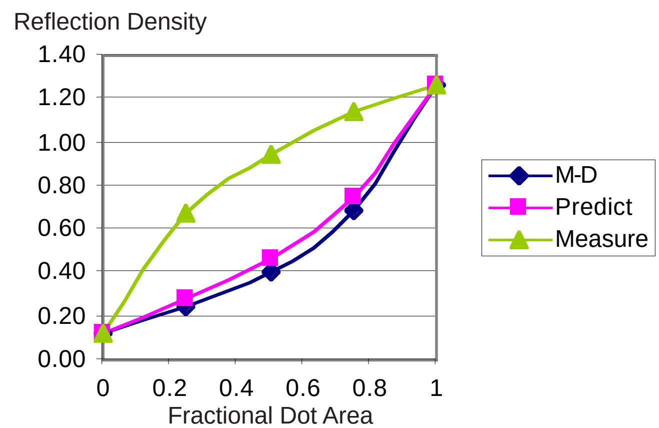


Figure 13. Reflection density of line screen 180 lpi printed on uncoated paper.

In our calculation the dot area is not the actual physical dot area on paper but is the digital dot area. Therefore the measure density is much higher than the calculation. The different between measurement density and density calculated by Murray-Davies equation is known as density gain and if we transform to dot area it is the apparent dot gain. In most printing system, this apparent dot gain must be compensate by creating an look up table for the halftone tranformation process. As the reflection density is not predicted well, We have to look back that whether MTF_{pr} can be a parameter to represent mechanical and optical dot gain. MTF_{pr} or associated *Rpsf* seems to affect to halftone image array the same way as PSF of paper does. Furthermore its effect is lower than the PSF of paper. Therefor those models must be modified in order to predict mesurement reflection density.

Conclusion

The MTF of Ink jet images were measured by three measurement methods. Those obtained MTFs were analyzed and compared by different method, paper type and printing direction. The relationship among MTF of print, MTF of image caused by ink spread and MTF of paper is not linear and is rather complex.

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Biography

Chawan Koopipat received his BSc. in Photographic Science and Printing Technology from Chulalongkorn University, Thailand in 1989 and MPhil in the work titled The Effect of the Increase of Dot Gain on Colour and Its Relationship with Colour Tolerances of Various Picture Contrasts from University of HertfordShire, UK in 1993. At present he is a doctoral student at Miyake laboratory, Chiba University, Japan. His works focus in the area of image quality evaluation.