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

Chawan Koopipat*, Norimichi Tsumura,▲ Makoto Fujino†, Kimiyoshi Miyata, and Yoichi Miyake✦

Graduate School of Science and Technology, Chiba University, Inage-ku, Chiba, Japan

† *Seiko Epson Corporation, Shiojiri-shi, Nagano, Japan*

In this study, the modulation transfer functions of prints, which included both mechanical and optical dot gain effects were measured from samples printed by an ink jet printer on glossy-coated, matte-coated and uncoated papers. The MTF of prints were measured from sinusoidal patterns and Fourier transforms of line spread functions from one-pixel line and step images. The MTF of prints by three measurement methods were analyzed and compared. The one-pixel line method was chosen to compare MTF of prints on different types of papers and printing directions. In addition, MTF of papers were also measured by contact sinusoidal pattern on papers. The point spread function of ink on each paper was estimated by using the measured point spread function of paper in the reflection image model. The results showed that glossy-coated ink jet paper had low MTF of paper but high MTF of print. Finally, printed densities of ink jet images were predicted using the estimated point spread function of ink and measured point spread function of paper. Because the spread function of ink was estimated as having a Gaussian distribution, which does not correctly represent the real point spread function of ink jet printing, the predicted density did not fit well with the measured density.

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Introduction

Ink jet printing is widely used because of its low cost and acceptable image quality. When an ink dot is printed on paper, there will be an important phenomenon called dot gain. This significantly affects sharpness, tone and color reproduction of a printed image. There are two types of dot gain: mechanical and optical, these are caused by lateral spread of ink on paper and lateral scattering of light in paper respectively. To achieve a good image quality, dot gain must be allowed for, before or during the process of transformation to halftone image. Yule and Neilsen[1] first introduced the *n* factor to account for optical dot gain. The *n* factor depends on halftone frequency and interaction properties of ink and paper. Arney[2] and co-researchers expanded the Murray–Davies model and separately modeled mechanical and optical dot gain effects. Since these are empirical models, some theoretical models of light scattering within the paper have also been studied.[3–6] The light scattering property of a paper can be known by measuring its point spread function. In practice, the modulation transfer function (MTF) is usually used to represent the point spread function of paper (psf_p) in the frequency domain. While the MTF of paper (MTF_p) can be measured by several techniques,[7–9] relatively little work has been done on measuring the point spread function of ink (psf_i). It is very difficult to measure only the psf_i because reflection from halftone image observed by an optical system always includes optical dot gain. Measuring the MTF of print (MTF_{pr}), will include both mechanical and optical dot gain effects.

In this article, the reflection image models are first described because they are the fundamental models used for measurement and analysis of MTF_{pr}. The experiment was carried out to compare three measurement methods for MTF_{pr}. The MTF_{pr} measurements were analyzed and compared according to paper type and printing direction. The psf_i results from three types of papers were calculated from psf_p and the models. Finally, reflection densities from line screen patterns were predicted by the calculated psfi and the measured psf_p.

Reflection Image Model

Reproduction of an image can be considered as having two parts, the first is the image formation on the substrate and the second is the image detection by an optical system. The image forming process is described by Fig. 1(a). A digital file, *f(x,y)*, which is a halftone image and has only 0 (no ink) or 1 (ink) value is sent to the printer in order to print ink dots on the substrate (usually paper). In reality, the actual dot size on the paper is larger than the digital dot size. The image that includes mechanical dot gain is modeled by the convolution integral of the original digital image with psf_i. The model[6] in Eq. 1 expresses the two dimensional transmittance of the ink layer that is printed on paper:

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▲ IS&T Member

✦ IS&T Fellow

* Phone: +81-43-290-3262, Fax: +81-43-290-3262; E-mail: chawan@icsd6.tj.chiba-u.ac.jp

† Phone: +81-263-54-2753, Fax: +81-263-54-4009

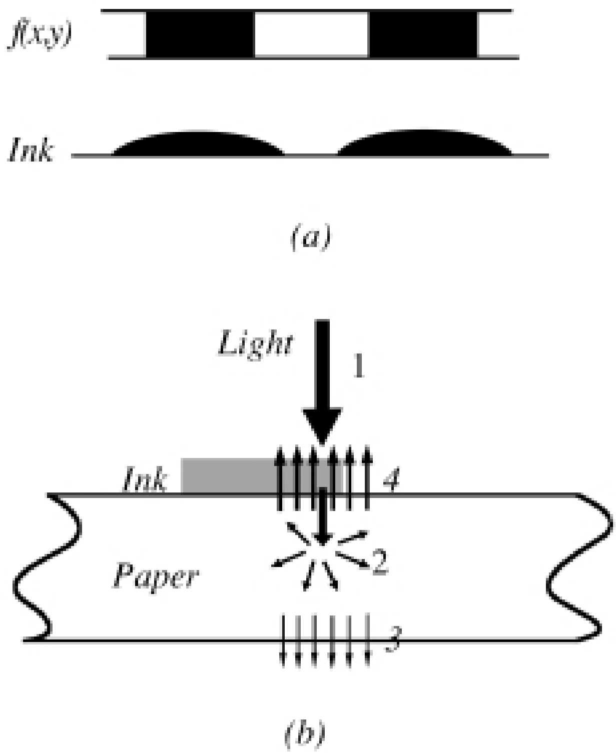

Figure 1. Schematic diagram of (a) the forming of ink layer and (b) the reflection image of a printed half-tone.

$$t(x,y) = 10^{-\left\{D_{\max}\left[f(x,y)*psf_i(x,y)\right]\right\}}, \tag{1}$$

where $D_{\max}$ is the transmission density of the solid area. The edge of the halftone dot will be smeared out by psf_i which is approximately expressed by Eq. 2,

$$psf_i(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{\left(x^2+y^2\right)}{2\sigma^2}}, \tag{2}$$

where σ denotes standard deviation of the distribution of ink.

Figure 1(b) is the schematic diagram of reflection of light from a printed image. For simplicity, it is assumed that the image (ink) layer sits on top of the paper surface and also that the incident light (i_{in}) and the reflectance of paper $r_p(x,y)$ are uniform. The perceived reflectance from an image can be explained as follow:

Step 1: Incident light (i_{in}) enters the ink layer.

Step 2: The ink layer with transmittance $t(x,y)$ absorbs some of the incident light.

Step 3: The transmitted light ($i_{in}\, t(x,y)$) scatters in the paper. In this step, the process can be represented by the convolution of transmitted light and normalized point spread function of paper ($i_{in}\, t(x,y)$)*($psf_p(x,y)$). Some scattered light will pass through the bottom surface of paper and most of the scattered light will emerge from top surface ($[i_{in}\, t(x,y)*psf_p(x,y)]r_p(x,y)$)

Step 4: The reflected light after scattering by paper is absorbed by the ink layer again. The reflected light from the image can be expressed as in Eq. 3,

$$i_{out} = \left[i_{in} t(x,y) * psf_p(x,y)\right] r_p(x,y) t(x,y). \tag{3}$$

When paper base reflectance is normalized as unity, Eq. 3 is reduced to:

$$r(x,y) = \left\{\left[t(x,y) * psf_p(x,y)\right] t(x,y)\right\}, \tag{4}$$

where $r(x,y)$ is the normalized reflectance of image. Equation 4 can be also expressed by reflection density as in Eq. 5,

$$Dr(x,y) = -\log\left\{\left[t(x,y) * psf_p(x,y)\right] t(x,y)\right\}. \tag{5}$$

A study by Inoue and co-workers[8] indicated that psf_p was exponential, as approximated by Eq. 6. Its corresponding MTF_p is expressed by Eq. 7,

$$psf_p(x,y) = \frac{1}{2\pi d^2} e^{\frac{-\sqrt{x^2+y^2}}{d}}, \tag{6}$$

$$MTF_p(\omega) = \frac{1}{\left[1+\left(2\pi d\omega\right)^2\right]^{3/2}}. \tag{7}$$

where d is a coefficient accounting for light scattering in the paper.

Measuring MTF of Print from Ink Jet Image

The MTF of an imaging system is directly obtained by measuring the reduction of modulation as a function of spatial frequency. In this technique, a sinusoidal pattern is usually used as input and measurement has been done on the output sinusoidal. A sinusoidal pattern was created which consisted of eight different frequency patches, 0.25, 0.50, 1, 2, 4, 6, 8 and 10 cy/mm respectively at a sampling rate of 720 pixels per inch (ppi). It was transformed to halftone image by an error diffusion algorithm before sending to the printer. Another alternative MTF is obtained by applying Fourier transform to the line spread function of a system. This technique was used to calculate MTF_{pr} by measuring line spread functions from one-pixel line and step images. The halftone sinusoidal, one-pixel line and step images were printed by an ink jet printer, an Epson PM770C, at 720 × 720 dots per inch (dpi) on glossy-coated, matte-coated and uncoated paper (see Fig. 2). The reflectance values, $r(x,y)$, from printed images were measured by a microdensitometer (Konica PDM-5) with aperture 1000×25 μm at 5 μm intervals. The scanning reflectance which normalized to the white paper, $i(x)$, from sinusoidal patterns, one-pixel lines and step images are related to the reflectance of images by Eq 8.

$$i(x) = \int r(x,y)\,dy. \tag{8}$$

Sinusoidal Method

The MTF_{pr} by sinusoidal method was calculated by Eqs. 9 and 10.

$$MTF_{pr_{\sin}}(\omega) = M(\omega) / M'(\omega), \tag{9}$$

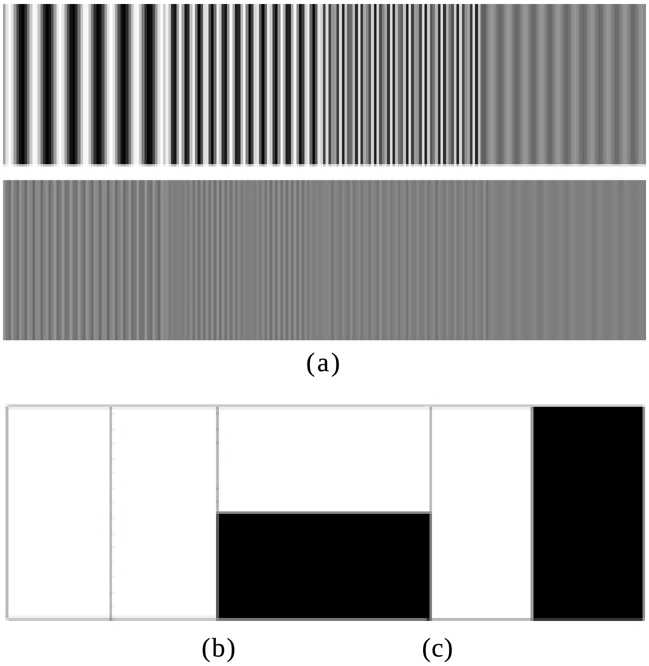

Figure 2. Experimental images (a) sinusoidal pattern (b) one-pixel line image and (c) step image

$$M(\omega) = \frac{i_{\max}(\omega) - i_{\min}(\omega)}{i_{\max}(\omega) + i_{\min}(\omega)}, \tag{10}$$

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 1.0. The $i_{\max}(\omega)$ and $i_{\min}(\omega)$ are the average peak and bottom of scanning reflectances from the image. Figure 3 shows the reflectance at some spatial frequencies from a sinusoidal halftone image printed on glossy-coated paper.

One-Pixel Line Method

The MTF_{pr} of the one-pixel line method was calculated by Eqs. 11 and 12,

$$MTF_{pr_{line}} = \left| \int lsf_{line}(x) e^{-j2\pi\omega x} dx \right|, \tag{11}$$

where $lsf_{line}(x)$ denotes the line spread function obtained by

$$lsf_{line}(x) = 1.0 - i_{line}(x), \tag{12}$$

where $i_{line}(x)$ is the normalized reflectance of one-pixel line image. Figure 4 shows the line spread function of one-pixel images on three types of paper.

Step Image Method

The MTF_{pr} of the step image method was calculated by Eqs. 13 and 14,

$$MTF_{pr_{step}} = \left| \int lsf_{step}(x) e^{-j2\pi\omega x} dx \right|, \tag{13}$$

where $lsf_{step}(x)$ denotes the line spread function obtained by the following formula,

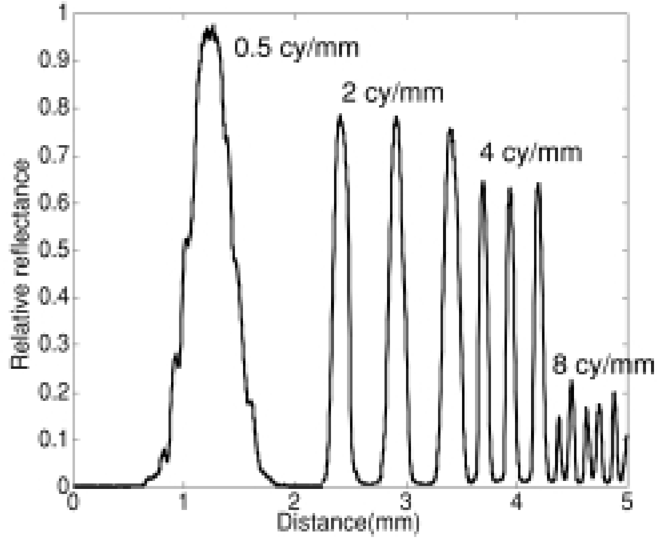

Figure 3. Relative reflectance from halftone sinusoidal image at spatial frequency 0.50, 2, 4 , and 8 cy/mm on glossy-coated paper.

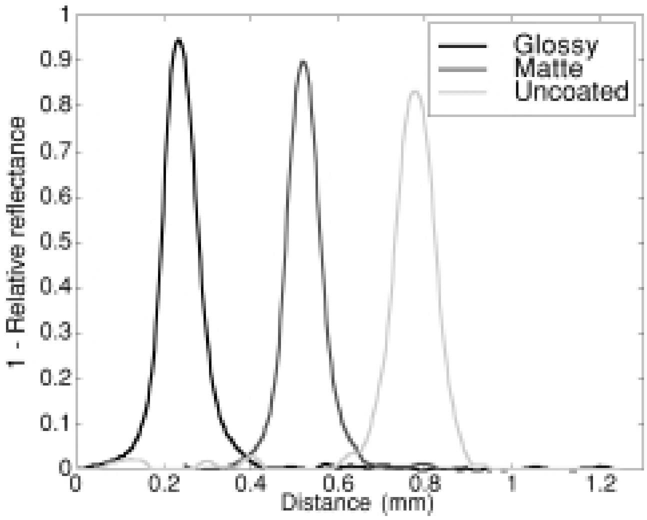

Figure 4. Line spread function from one-pixel line images printed on glossy, matte and uncoated paper.

$$lsf_{step}(x) = \frac{d(s(x))}{d(x)}, \tag{14}$$

where $s(x)$ is the normalized reflectance of the edge trace from step image. Figure 5 shows the calculated line spread function of three types of paper.

Comparison of MTF of Print Measurement Method

The MTF_{pr} values measured from these three methods were corrected by the MTF of the microdensitometer obtained from a Fourier transform of scanning width. The MTF at 10 cy/mm is about 90% and the corrected MTF_{pr} values from the three measurement methods are shown in Fig. 6.

Figure 6 shows that the MTF calculated from the sinusoidal method is higher than from the one-pixel line

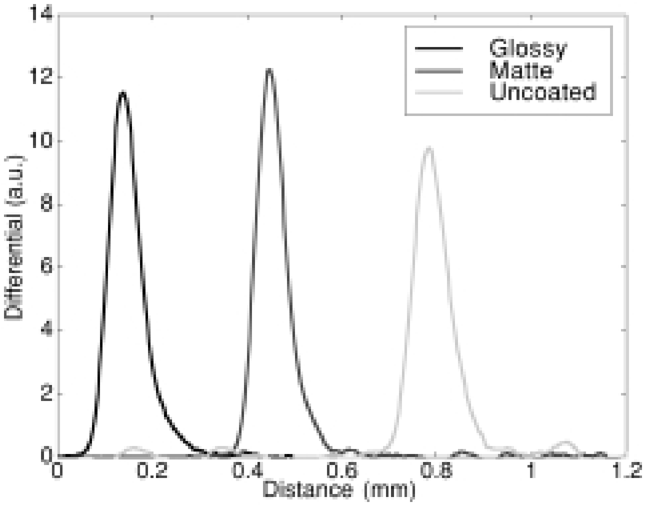

Figure 5. Line spread function from step images printed on glossy, matt and uncoated paper.

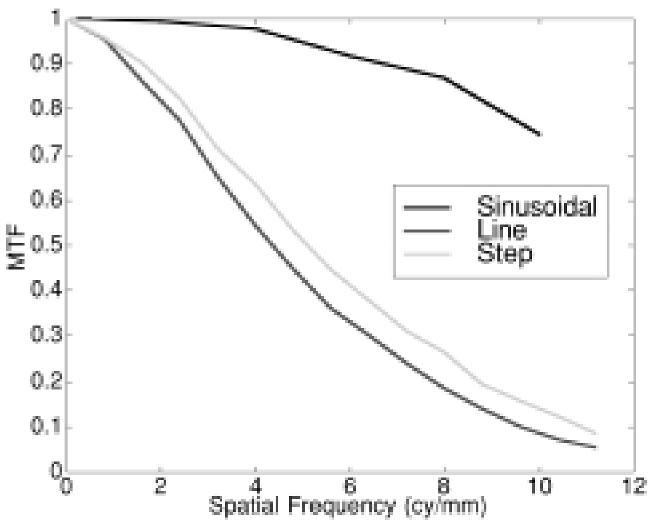

Figure 6. MTF_{pr} from sinusoidal, one-pixel line and step image printed on glossy-coated paper.

and step methods. The reason is that the printed sinusoidal is a halftone image, thus the i_{min} does not increase with frequency as much as the continuous tone sinusoidal usually does. Consequently, the calculated output modulation is higher than it should be. Therefore, we can conclude that it is not an adequate method for measuring MTF_{pr}. The measurements of one-pixel line and step image are simple because only one measurement is required for each image. Note that MTF_{pr} values measured from one-pixel line and step images do not include MTF of halftone pattern. With this in mind, we can use MTF_{pr} to evaluate print quality that relates to the point spread function of ink and point spread function of paper.

Between these two methods, the one-pixel line method was chosen to analyze the MTF_{pr} from different types of paper and printing directions because the point spread function of ink is directly represented by the one-pixel line method. As the edge of the step image is constructed

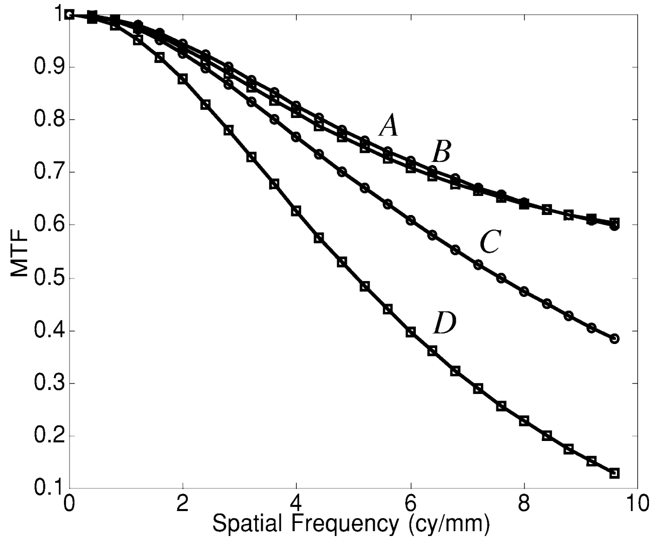

Figure 7. Simulated MTF_{pr} from delta function and step image method, MTF_{pr} were calculated from the models using d value = 0.03 and setting psf_i as follow: Case A: MTF_{pr} from step image, no ink spreading; Case B: MTF_{pr} from one-pixel line, no ink spreading; Case C: MTF_{pr} from step image, σ = 0.02; Case D: MTF_{pr} from one-pixel line, σ = 0.02

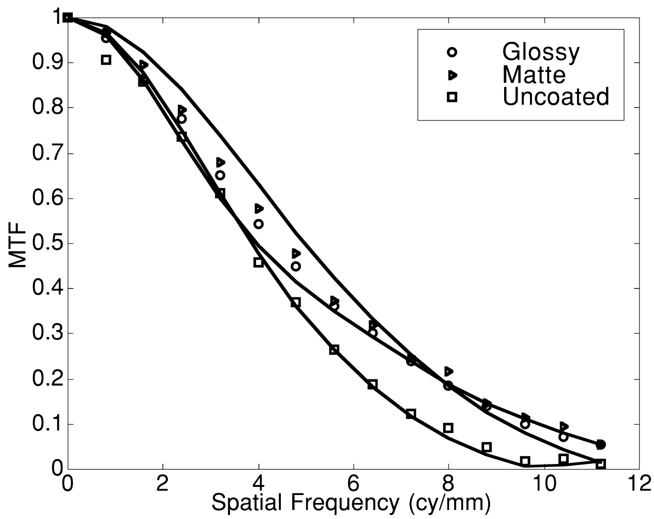

Figure 8. MTF_{pr} from one-pixel line images printed on glossy-coated, matte-coated and uncoated paper. The lines are the calculated MTF_{pr} from a model with σ values equal to 0.018, 0.21 and 0.029 for glossy-coated, matte-coated and uncoated paper respectively.

from the overlapping of several discrete dots, the MTF_{pr} values measured from these edges will be higher than from the one-pixel line. If the printer could produce an infinitely small dot, and there was no ink spreading, the MTF_{pr} measured by both methods would be the same, as shown by the simulation in Fig. 7.

Type of Paper

When we compared MTF_{pr} from vertical edge images shown in Fig. 8, uncoated paper shows the lowest MTF. The MTF_{pr} of glossy-coated paper is slightly lower than matte-coated paper.

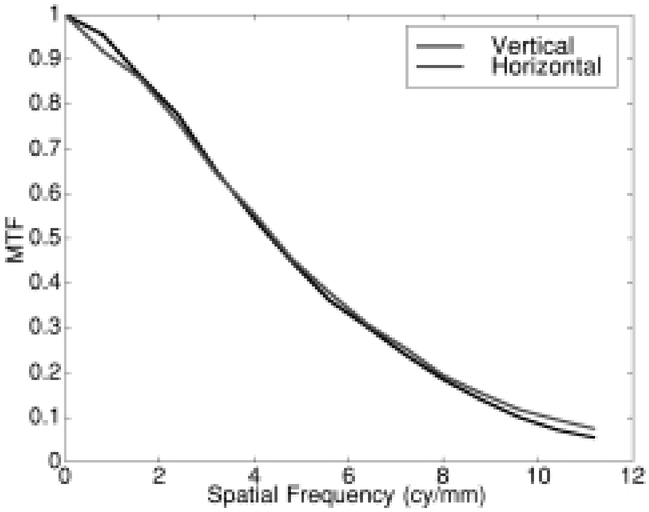

Figure 9. MTF_{pr} from one-pixel line images in vertical and horizontal printing direction, printed on glossy-coated paper.

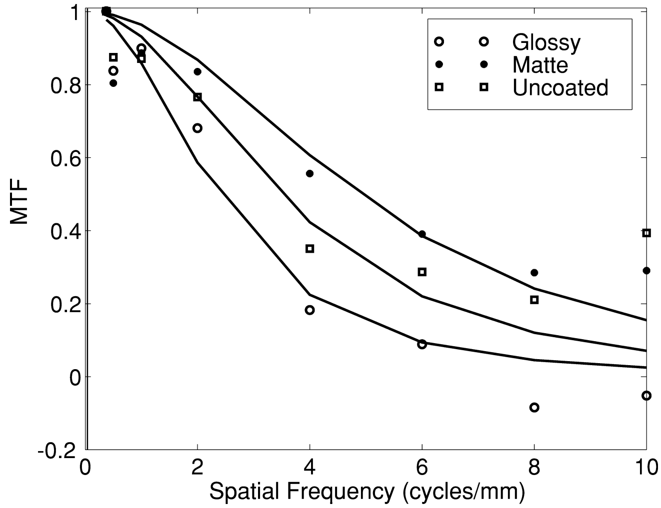

Figure 10. MTF_p from contact sinusoidal pattern film on glossy, matte and uncoated paper. The solid lines are calculated by the model in Eq. 7 with d values 0.052, 0.025 and 0.035 respectively.

Printing Direction

Figure 9 shows very small differences in MTF_{pr} measured across glossy-coated paper. If we assume glossy-coated paper is isotropic, we can conclude that the sharpness of a printed image is similar along vertical and horizontal printing directions.

Measuring MTF of Paper

Because MTF_{pr} included the effect of mechanical and optical dot gains, therefore we need to measure only MTF_p in order to separately analyze both effects on the printed image. The contact sinusoidal pattern technique[10] was used to measure contrast transfer function (CTF) of paper. The calculation from CTF to MTF was carried out by combining Eqs. 15 through 17.

The contrast $C(\omega)$ is the difference between peak and bottom of normalized reflection intensity at ω frequency. This can be obtained from scanning a sinusoidal film contacted on a paper by a microdensitometer. We used scanning aperture at 1000×25 µm with 5 µm intervals. The measured CTF values were corrected by the system MTF. The system MTF was measured from scanning only the sinusoidal test film and the MTF was obtained by Eq. 9 and Eq 10. The MTF_p from glossy-coated, matte-coated and uncoated paper are shown in Fig. 10. The solid lines were calculated from Eq. 7 by selecting d values that gave the minimum RMS error. The d values for glossy-coated, matt-coated and uncoated paper are 0.052, 0.025 and 0.035 respectively.

$$MTF_p(\omega) = 2 \cdot CTF(\omega) - 1, \tag{15}$$

$$CTF(\omega) = \frac{C(\omega)}{C(0)}, \tag{16}$$

$$C(\omega) = I_{\max}(\omega) - I_{\min}(\omega). \tag{17}$$

Calculation of Point Spread Function of Ink

Because d values are known from the measurement of MTF_p and D_{max} from the square root of solid density, a program was written by using Eqs. 1, 2, 4, 6, 11, and 12 to calculate the MTF_{pr} from one-pixel line data. The σ value in Eq. 2 was selected to give the best fit between the calculated MTF_{pr} and the measured MTF_{pr}. The continuous curves in Fig. 8 are the results from the calculations.

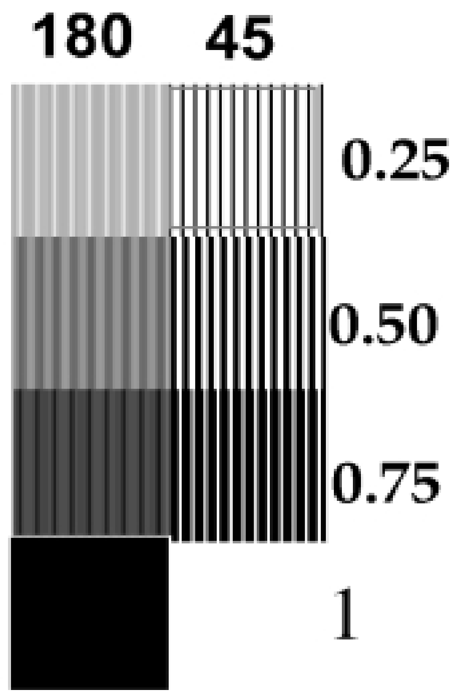

Figure 11. The line screen test pattern at 45 and 180 lpi.

Prediction of Reflection Density

A line screen pattern was created with screen frequency 45 and 180 lpi as shown in Fig. 11. These patterns were printed on glossy-coated, matt-coated and uncoated paper. A Sakura densitometer (PDA-65) was used to the measure density of each patch (45/0 degree measure-

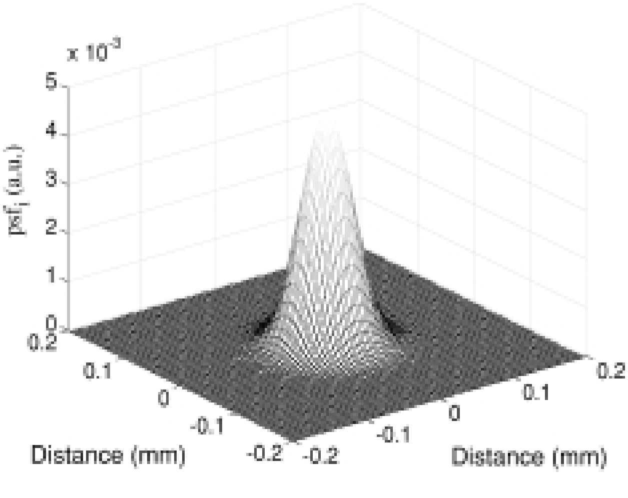

Figure 12. Normalized psf_i with σ = 0.029.

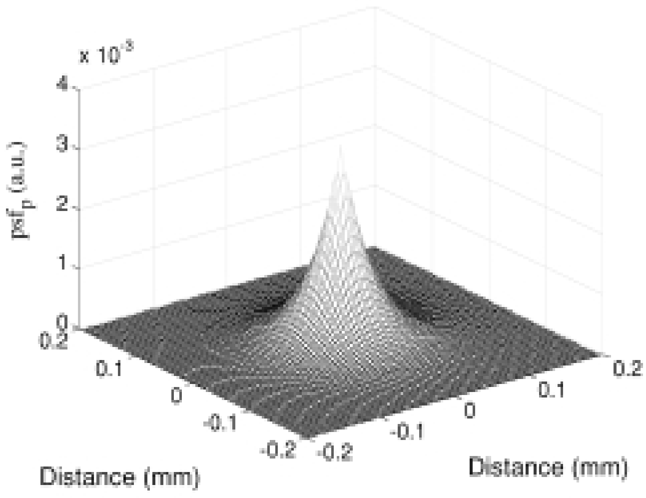

Figure 13. Normalized psf_p with d=0.035.

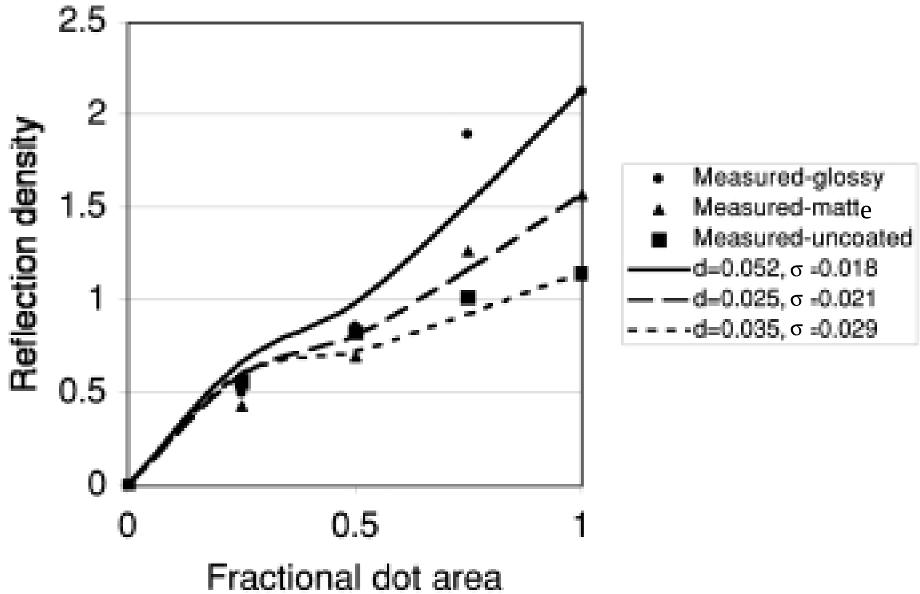

Figure 14. The fitting of measured density with predicted density of line screen 180 lpi printed on glossy-coated paper, matte-coated paper and uncoated paper. The *d* values were from the measurement from contact sinusoidal method and σ values were from the prediction.

ment geometry). The predicted densities were calculated using Eqs. 1 through 6. The examples of normalized $psf_i(x,y)$ and $psf_p(x,y)$ values are plotted in Fig. 12 and Fig. 13. The predicted densities compared with the measured densities are shown from Fig. 14 and Fig. 15.

Discussion

When considering the MTF_{pr} from Fig. 8, the glossy-coated paper has a lower MTF than matt-coated paper but higher than uncoated paper. In Fig. 10, the MTF_p from glossy-coated paper is the lowest. This indicated that glossy-coated paper has allowed ink spread less than the other two papers because its MTF_{pr} improved significantly. We also can observe this behavior from the σ values. However, the calculated MTF_{pr} values from the model did not fit well with the measured MTF_{pr} values especially for inkjet papers. The main reason might be that the Gaussian function was used to represent psf_i, which is not true for the ink jet paper. An article by Emmel and Hersch[11] stated that ink spreading for ink jet printers was parabolic. We intend to improve the estimation of psf_i in further research.

The measured MTF_{pr} from all papers are higher than MTF_p .This is expected because the reflected light from the halftone image is filtered by the second $t(x,y)$, this will sharpen the reflected blur image caused by point spread function of paper. Therefore, when we measure the MTF_{pr} the result will be higher than the MTF_p. Another reason for this is that ink not only spreads but also penetrates into paper. When ink penetrates the paper, the distance between ink and background will decrease, therefore the probability of light scattering in paper will decrease. We can also observe from Fig. 14

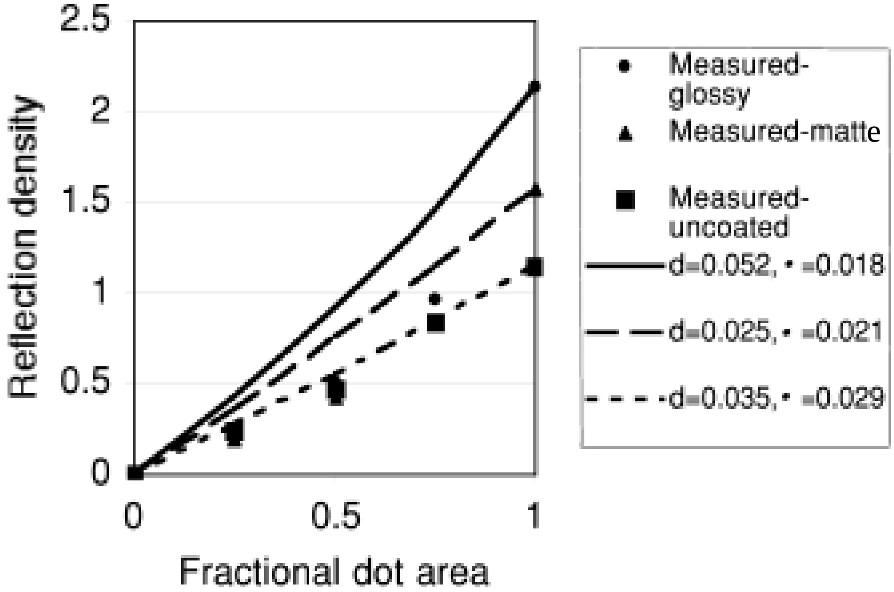

Figure 15. The fitting of measured density with predicted density of line screen 45 lpi printed on glossy-coated paper, matt-coated paper and uncoated paper. The *d* values were from the measurement from contact sinusoidal method and σ values were from the prediction.

and Fig. 15 that the reflection density is not well predicted by the model. In the prediction process, there are two important parameters, the point spread function of ink and point spread function of paper. As the point spread of paper is obtained from the MTF of paper using the contact sinusoidal method, the error in measurement is quite high. Furthermore, measurement geometry of the densitometer is 45/0 in contrast to the simulation that assumes isotropic distribution of light, therefore the measurement density might not be well predicted by the simulated density. In addition, we assumed that ink spread function is gaussian and has isotropic properties, which is not true in real life.

The distribution of ink on the substrate depends on several factors: point spread function of ink, which affects the dot diameter and edge fringe: the overlapping of each dot, which affects the sharpness of text and line; the volume of the ink dot which affects graininess and maximum density; the halftoning algorithm, which affects the tone and color reproduction of the picture. Therefore we are now studying how ink is distributed on the paper surface in order to find a more accurate model to estimate reflection density of a printed image.

Conclusion

The MTF of print from ink jet images were measured from printed sinusoidal, one-pixel line and step images. The MTF of print measured from one-pixel line image indicated that images printed on ink jet paper had better quality compared with normal uncoated paper as a result of its lower point spread function of ink. For vertical and horizontal printing direction, the experimental printer showed very similar MTF. The prediction of the density of printed image using the reflection image model was not good. Further study will be required to improve the model.

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