Effect of Ink Spread and Opitcal Dot Gain on the MTF of Ink Jet Image

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A new measurement method is proposed to separately measure the effect of ink spread and optical dot gain on the MTF (modulation transfer function) of printed images from an ink jet printer. The transmittance and reflectance of the same printed images are captured with two different illuminations: one on the printing surface (for measuring reflectance) and the other through the paper base surface (for measuring transmittance). The MTF of ink image and MTF of print are measured from one-pixel line printed on glossy, matte and uncoated paper. The result shows that the paper type significantly affects the MTF of ink image and the MTF of print. The MTF of paper is also measured by this method and it is shown that optical dot gain considerably affects the MTF of print.

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Introduction

The modulation transfer function (MTF) is a standard figure of merit used to estimate the image quality of an imaging system. For a photographic system, the MTF is usually measured to represent the detail recording of optical system, photographic material and etc. The input signal in this system is the exposure, and output is the density obtained from transmittance of developed film or reflectance of developed paper.[1] For the ink jet printing system, which is a discrete process, the input is the digital count, and the output is the average reflectance or density of the halftone ink image on the paper. The output from the printing system is strongly nonlinear to the input because the effect of dot gain.

Dot gain is defined as the increase of the dot size of the final output over the initial size. This makes the printed image appear darker (more intense color) than intended. In conventional printing such as offset printing, the initial size of the halftone dot is the dot size in the color separation film. However, there is no film in digital printing, therefore the nominal size of dot intended by the printing process (geometric area defined by the bit values) is usually used as the initial dot size.[2] There are two types of dot gain: one is mechanical dot gain which is defined as the increase of dot size from the spread of ink on the paper surface, the other is optical dot gain which is defined as the increase of dot size from the loss of reflectance according to light scattering in the paper.

The optical dot gain has been studied for many decades and many measurement techniques have been proposed to measure MTF of paper.[3–6] However, relative little work has been done on mechanical dot gain because it has less effect on image quality. This is true for many printing technologies such as offset and electrophotography which the ink is not in a liquid form. However, this is not the case for ink jet printing which has high ink spread function. In the ideal case, the printed dot size from a commercial 720 dpi printer on a high quality ink jet paper should have the diameter of approximately 35 μm. However when observed through a microscope, the printed dot diameter is about 70 μm. To evaluate the image quality of the ink jet printing, ink spread on the paper must be taken into consideration. The quality of ink image on paper is dependent on printer resolution, halftoning technique, viscosity of ink, paper properties, etc. To evaluate the effect of each factor on image quality, we need to separate the ink spread from the optical dot gain. The problem is that measuring ink dot image (area) on paper always includes the optical dot gain. The method that is usually used to measure the ink image without optical dot gain is to print a halftone image on transparency, and the printed image is observable when the transparency is in optical contact with the paper.[7] However, this is not applicable if the coated layer on the transparency has different absorption properties to those of the coating on the printed paper.

In this article, we propose an approach to separately measure the ink image on the paper without the effect of optical dot gain. With this proposed method, the MTF of ink image and MTF of print are measured from the printed one-pixel line image. The MTF of paper are measured from the contact of a sharp edge on paper. Those measured MTFs are analyzed and compared.

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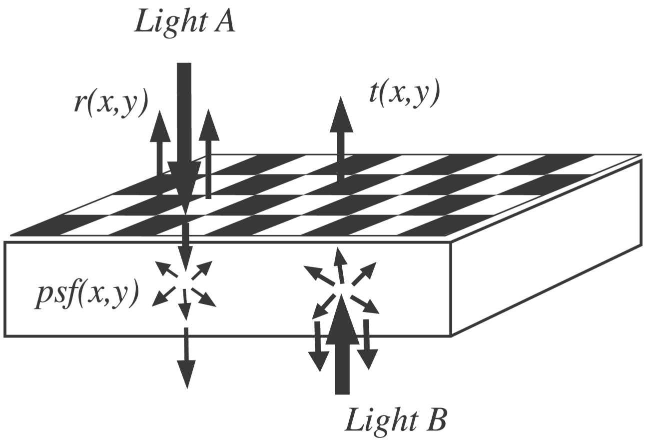

Figure 1. Schematic diagram of reflectance and transmittance from a halftone image.

Measurement Instrument

The method of measuring ink image transmittance on the paper without the effect of optical dot gain is to illuminate a printed sample by two light sources. One illuminates the printing surface (measuring reflectance), and the other illuminates from the paper based surface (measuring transmittance) as shown in Fig. 1. The reflected image is the image that includes ink spread and the optical dot gain effect, while the transmitted image has only the ink spread effect.

The instrument consists of a monochrome digital camera (Kodak DCS420) attached to a microscope (Fig. 2). The effective resolution of CCD sensor in this camera is 1012 × 1524 pixels with 9 μm pitch and the magnification of the optical system is X10. Two polarizing filters are used, one in front of the light source and the other in front of the camera sensor in order to eliminate the specular reflection, because the measurement geometry is 0/0 degree. The light source A and B are adjusted independently to normalize to the bare paper. This is done by fixing the shutter speed of the camera and setting the light intensity that the average pixel value of reflectance and transmittance of the bare paper close to 250.

By capturing the reflectance and transmittance of a one-pixel line image, the MTF of ink image and MTF of print can be obtained. In addition, the MTF of paper from various types of paper also can be calculated based on image reflectance and transmittance models.

Image Reflectance and Transmittance Model

Recently, halftone reflectance has been modeled by two approaches, the probability approach[8,9] and the convolution approach.[10–13] In our study we use the convolution approach which defines reflectance of a halftone, $r(x,y)$, as follows:

$$r(x,y) = \{[t(x, y) * psf\,(x,y)]t(x,y)\}, \tag{1}$$

where $t(x,y)$ is the transmittance of ink on paper, $psf(x,y)$ is the point spread function of paper, and * denotes the convolution integral. From Fig. 1, when light A enters the printed halftone image on the printed surface, first it is filtered by the image transmittance $t(x,y)$. Then after penetration and scattering in the paper, it is filtered again with the $t(x,y)$ on the way back from the surface.

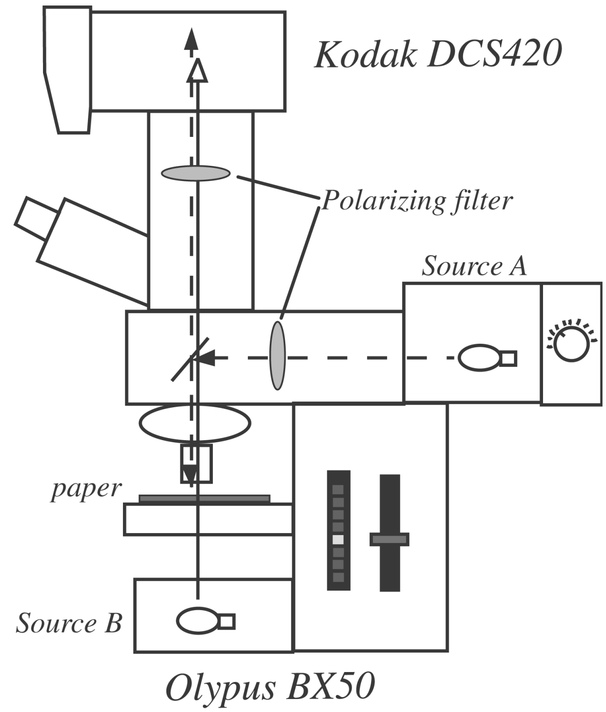

Figure 2. Measurement set-up.

Because paper is usually thin, it will transmit a portion of incident light. If we assume that the paper base is a perfect diffuser, the light B that enters paper from underneath will scatter and some parts will pass through the ink dot and emerge from the printed surface. This $t(x,y)$ is equivalent to $t(x,y)$ from the reflection illumination when both illuminations are normalized to base paper.

MTF of Ink Image

The ideal printer is able to print a very tiny dot that has zero reflectance (black ink). Without ink spread, a single dot profile will be a delta function. However, the real dot has some diameter, depending on the printer resolution, and ink volume, and also has irregular shape depending on the ink spread characteristic on the paper. Furthermore, the dot density is not uniform, especially at the edge of dot, therefore the one-pixel line image will have the gradation at the edge. Since an ink jet printer has a limited resolution, the lower the resolution of the printer, the thicker the one-pixel line image is. To measure the MTF of ink image (MTF_i), we calculated from the Fourier transform of line spread function of one-pixel line image as shown in Eq. (2).

$$MTF_i(u) = \left| lsf_t(x) e^{-j2\pi ux} dx \right| \tag{2}$$

where $lsf_t(x)$ is the line spread function of one-pixel line image, and u denotes the spatial frequency. The line spread function of one-pixel line image is obtained from Eq (3).

$$lsf_t(x) = 1.0 - \int t(x,y)dy \tag{3}$$

where $t(x,y)$ is the transmittance of one-pixel line image. Figure 3 shows the $t(x,y)$ and $r(x,y)$ of one-pixel line image from three types of paper.

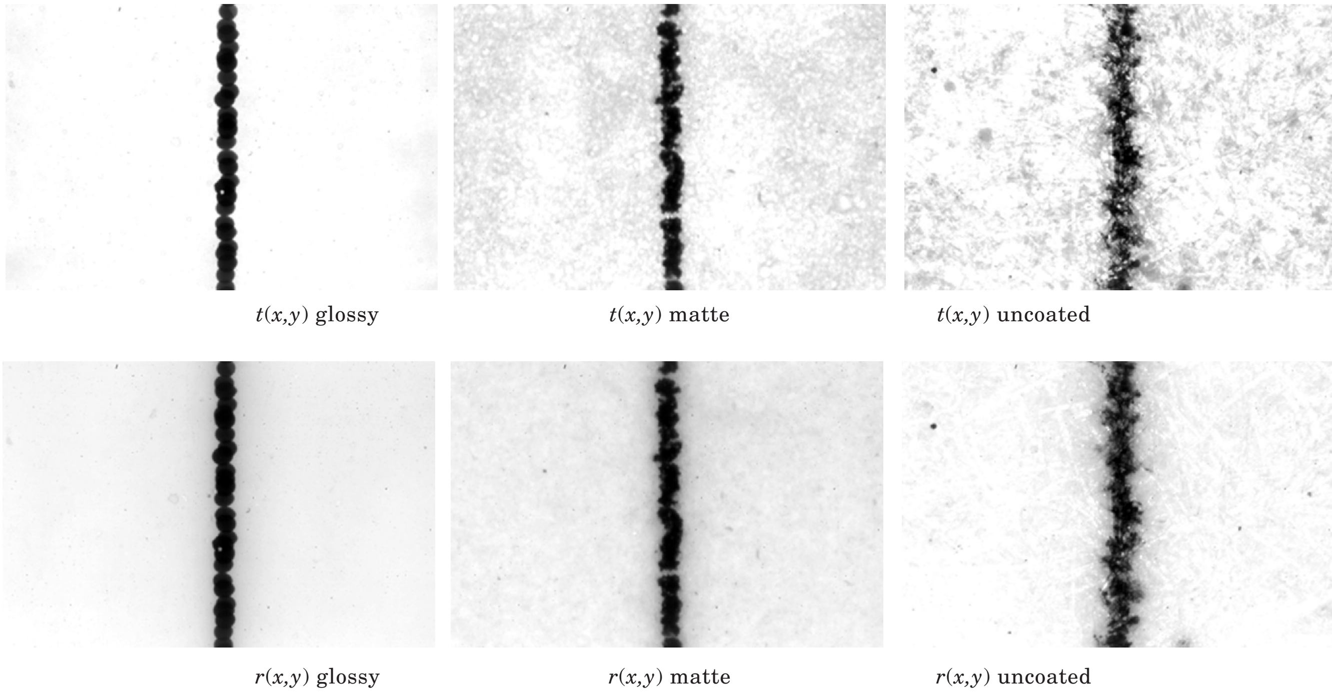

Figure 3. The $t(x,y)$ and $r(x,y)$ of one-pixel line image printed on glossy, matte and uncoated paper.

From the observation of $t(x,y)$ images, the paper structure on matte and uncoated paper will affect the MTF_i by adding edge gradient to the line spread function, therefore lower the actual MTF_i. To reduce the paper structure effect from MTF_i in the spatial frequency domain, we used Eq. (2) to calculate the MTF_i of one-pixel line image printed on a transparency that is in optical contact with those papers. Since we assumed that the glossy coated paper is a perfect diffuser, i.e., no paper structure, we then calculated the MTF_i of matte and uncoated paper from Eq. (4).

$$MTF_{i_n}(u) = MTF_{i_n}^{'}(u) + MTF_{structure_n}(u), \qquad (4)$$

where n denotes matte or coated paper, the refers to the measured MTF of ink from printed image and $MTF_{structure}$ is the difference of MTF value of glossy paper from matte or uncoated paper at u frequency which is obtained from Eq. (5).

$$MTF_{structure_n}(u) = \overline{MTF}\,i_{glossy}(u) - \overline{MTF}\,i_n(u), \qquad (5)$$

where $\overline{MTF}i$ is the MTF of ink image on transparency contacting with paper. The MTF_i of one-pixel line image printed on glossy, matte and uncoated paper are shown in Fig. 4.

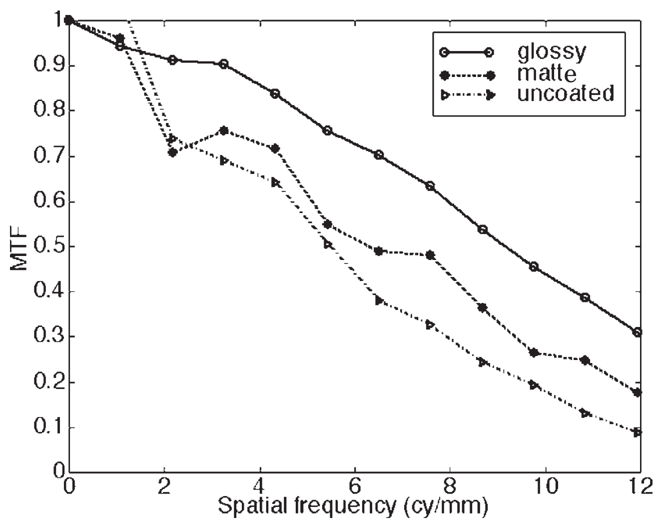

Figure 4. The MTF_i of one-pixel line image printed on glossy, matte and uncoated paper.

MTF of Print

Similar to the MTF of ink image, the MTF of print (MTF_{pr}) which is included the optical dot gain effect is calculated from the Fourier transform of line spread function of one-pixel line image as shown in Eq. (6)

$$MTF_{pr}(u) = \left| \int lsf_{pr}(x) e^{-j2\pi ux} dx \right|, \qquad (6)$$

where $lsf_{pr}(x,y)$ is line spread function obtained from Eq. (7).

$$lsf_{pr}(x) = 1.0 - \int r(x,y)dy \qquad (7)$$

Figure 5 shows the MTF_{pr} measured from three types of paper.

MTF of Paper

From the reflectance image model in Eq (1), if $r(x,y)$ is divided with $t(x,y)$ we can obtain Eq. (8).

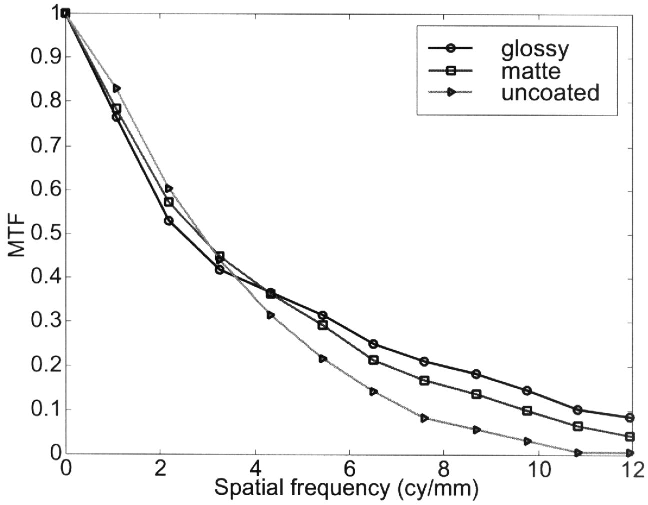

Figure 5. The MTF_{pr} of one-pixel line image printed on glossy, matte and uncoated paper.

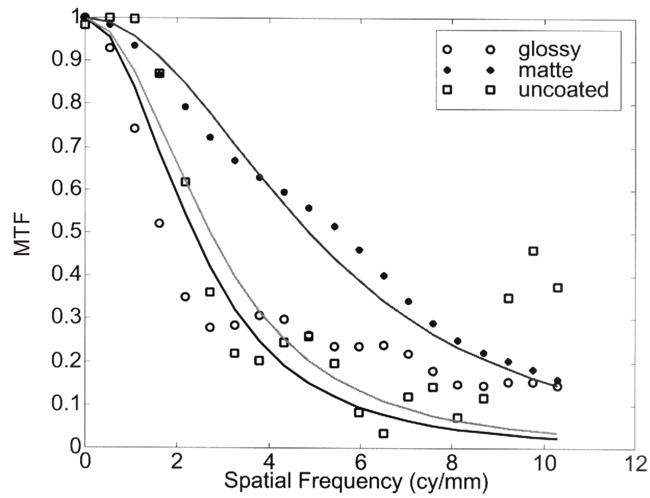

Figure 6. The MTF of paper measured from glossy, matte, and uncoated paper (see text for detail).

$$\frac{r(x,y)}{t(x,y)} = \left\{t(x,y) * psf_p(x,y)\right\} = t_{psfp}(x,y), \tag{8}$$

where $T_{psfp}(x,y)$ is the transmittance of image after scattering within the paper. Equation (9) is the Fourier transform of Eq. (8) and the MTF_p can be obtained by Eq. (10)

$$\left\{T(u,v) \cdot MTF_p(u,v)\right\} = T_{psfp}(u,v), \tag{9}$$

$$MTF_p(u,v) = \frac{T_{psfp}(u,v)}{T(u,v)}. \tag{10}$$

Because the paper is assumed to have isotropic properties, the one-dimensional MTF of paper can be obtained from Eq. (11).

$$MTF_p(u) = \frac{T_{psfp}(u)}{T(u)}. \tag{11}$$

Note that the MTF of the optical system of the microscope may be assumed to be unity because we are interested only in low frequencies (less than 10 cycles/mm). From Eqs. (8) through (10) if we know $r(x,y)$ and $t(x,y)$ we can calculate the MTF of paper. There are two alternatives in the measurement of $r(x,y)$ and $t(x,y)$. If we use the contact method, the MTF of paper will not include the effect of the penetration of ink into the paper. In contrast when using the printed image, the corresponding MTF of paper will include the effect of the penetration of ink into the paper. To compare with the previous measurement method of the MTF of paper, we used the sharp edge image on glass (Edmund Scientific) contacted on three types of paper. The edge spread function of $t(x,y)$ and $t_{psfp}(x,y)$ are calculated by Eq (12).

$$e_i(x) = \int t_i(x,y)dy \tag{12}$$

where i is $psfp$ or none, The line spread function, $lsf_i(x)$, is obtained from Eq. (13) and the $T(u)$ in Eq. (14) is the Fourier transform of line spread function.

$$lsf_i(x) = \frac{d(e_i(x))}{d(x)}, \tag{13}$$

$$T_i(u) = \left|\int lsf_i(x)e^{-j2\pi ux}dx\right| \tag{14}$$

Replacing the $T(u)$ and $T_{psfp}(u)$ from Eq (14) in Eq. (11) we can obtain the MTF of paper. The MTF_p of glossy, matte and uncoated papers are plotted in Fig. 6. The solid and dashed lines are the fitting curves from the empirical MTF model in Eq. (15). The d value is the coefficient account for the scattering distance of a point of light and ω denotes the spatial frequency in mm^{-1}. The corresponding point spread function of paper is given by Eq. (16).

$$MTF_p(\omega) = \frac{1}{\left[1+(2\pi d\omega)^2\right]^{3/2}}. \tag{15}$$

$$psf_p(x,y) = \frac{1}{2\pi d^2} e^{\frac{-\sqrt{x^2+y^2}}{d}}. \tag{16}$$

Discussion

Considering the effect of paper type on the MTF_i, it is obvious from Fig. 4 that glossy paper has the best quality because of the highest MTF_i, for example at 5 cycles/mm the MTF_i values of glossy, matte and uncoated paper are 0.80, 0.63 and 0.55 respectively. Since the ink dot volume is constant and the MTF_i at zero frequency is normalized to unity, therefore the differences in the MTF_i values come mainly from the spread of the ink on the paper.

From Fig. 5, the MTF_{pr} of each paper decreases significantly from the MTF_i because optical dot gain is involved. These results show that glossy paper has better MTF_{pr} values only at high frequency. In viewing the printed image, glossy paper will show finer detail than the other papers. The MTF_{pr} of glossy paper has de-

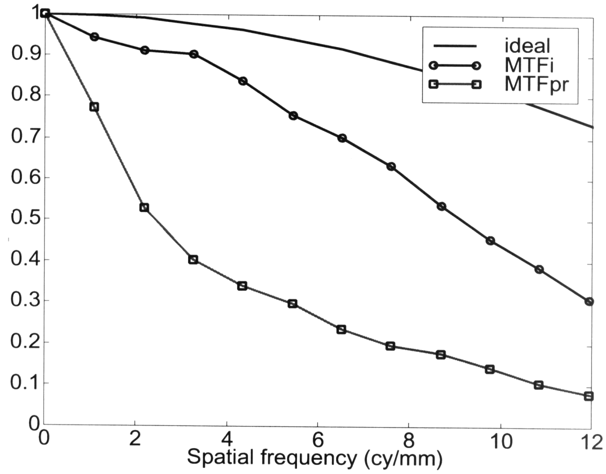

Figure 7. The comparison of ideal MTF_i, measured MTF_i and MTF_{pr} from glossy coated paper.

creased more than for the matte and uncoated papers because it has greater light scattering power. This is confirmed by the result in Fig. 6 which shows that the MTF_p of glossy paper is the lowest.

Figure 6 shows the measured MTF_p of three papers. The d values are 0.052, 0.025 and 0.045 for glossy, matte and uncoated paper, respectively. In the previous study,[14] we measured the MTF of paper by the contact of sinusoidal method. The d values were 0.054, 0.025 and 0.035 for glossy, matte and uncoated paper, respectively. The measurement method using a sinusoidal pattern is difficult because many measurements are required and the pattern alignment is critical to an accurate result. The merit of the presently proposed method is that only two images are required to obtain the MTF of paper and the instrument setting is quite simple. However this method yields a lot of noise, arising mainly in the differentiation of the edge spread function.

Figure 7 shows the comparison of printed MTF_i and MTF_{pr} of one-pixel line on glossy coated paper with the MTF_i of ideal one-pixel line image. The ideal one-pixel line is the simulated sharp line that has a width of 35 μm (1/720 dpi). The MTF_i of this ideal line is the highest MTF of ink image that this experimental printer can produce. The differences between the ideal MTF_i and printed MTF_i are caused by the ink spread and the differences between ideal MTF_i and MTF_{pr} is caused by both ink spread and optical dot gain. We can observe that not only the optical dot gain but also the ink spread significantly affect the MTF of the printed image.

Conclusion

We propose a new method of measuring and analyzing the MTF of ink image which is caused by the ink spread, and also the MTF of print which is caused by both ink spread and optical dot gain. The measurement results show that the differences in ink spread function and optical dot gain of the paper significantly affect the MTF of ink and the MTF of print of the ink jet images.

It is our objective to study the dot formation on the paper and others factors that affect image quality of ink jet printers. With this measurement method, once we know how the ink dot is distributed without the effect of optical dot gain, it may be possible to model all factors, i.e., ink volume, ink dot placement, ink spreading, ink penetration into the paper, and the halftone algorithm, that affect the appearance of the printed image on the paper.

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