PAPER

A Simple Method to Measure MTF of Paper and its Application for Dot Gain Analysis

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SUMMARY Image quality of halftone print is significantly influenced by optical characteristics of paper. Light scattering in paper produces optical dot gain, which has a significant influence on the tone and color reproductions of halftone print. The light scattering can be quantified by the Modulation Transfer Function (MTF) of paper. Several methods have been proposed to measure the MTF of paper. However, these methods have problems in efficiency or accuracy in the measurement. In this article, a new method is proposed to measure the MTF of paper efficiently and accurately, and the dot gain effect on halftone print is analyzed. The MTF is calculated from the ratio in spatial frequency domain between the responses of incident pencil light to paper and the perfect specular reflector. Since the spatial frequency characteristic of input pencil light can be obtained from the response of perfect specular reflector, it does not need to produce the input illuminant having "ideal" impulse characteristic. Our method is experimentally efficient since only two images need to be measured. Besides it can measure accurately since the data can be approximated by the conventional MTF model. Next, we predict the reflectance distribution of halftone print using the measured MTF in microscopy in order to analyze the dot gain effect since it can clearly be observed in halftone micro-structure. Finally, a simulation is carried out to remove the light scattering effect from the predicted image. Since the simulated image is not affected by the optical dot gain, it can be applied to analyze the real dot coverage.

key words: *MTF, paper, halftone print, dot gain*

1. Introduction

Image quality of halftone print is significantly influenced by a scattering characteristics in paper. Because of the scattering in paper, a photon would emerge the print from a different position of the halftone microstructure where it entered, and printed dots are perceived bigger than intended by observers. This phenomenon is known as the optical dot gain or the Yule-Nielsen effect. The optical dot gain makes the tone of halftone print appear to be darker, and it affects not only the tone reproduction but also the color reproduction [1]. The light scattering in paper can be quantified by the paper's point spread function (PSF) or, equivalently, the paper's modulation transfer function (MTF). The PSF is the optical impulse response of paper. The MTF is defined as the modulus of the Fourier transform of the PSF. Several researchers have proposed the method to measure the MTF of paper. Inoue *et al.* propose a method to project sinusoidal test patterns and measure the ratio of modulation depth of these patterns, respectively [2]. This is the most direct method for measuring the MTF therefore the measured data would be accurate. However, it requires to project and measure iteratively a lot of sinusoidal test patterns having different spatial frequencies. Inoue *et al.* propose another method not to project but to contact sinusoidal test target printed on film [3]. This method is experimentally more simple than the projecting method but it remains to need measuring several patterns iteratively. As more efficient methods, Yule *et al.* [4], [5], Engeldrum and Pridham [6], and Atanassova and Jung [7] measured the line spread function (LSF) of paper from the edge spread function (ESF) obtained by the knife edge projection method. If the light scattering in paper is assumed isotropic, the imaging properties are specified either by the PSF, LSF, or MTF in the spatial frequency domain. Their methods are experimentally more efficient than the sinusoidal test patterns method since only one projected edge image needs to be measured. However, the measurement accuracy is not well since the noise in the knife edge response is increased when the derivation is calculated to obtain the LSF from the ESF. Rogers proposes a series–expansion bar–target technique [8]: a bar–target image data is projected on paper and the response is measured. He calculated the ratio between the series–expansion coefficients of the Fourier transform of measured data and that of ideal bar–target data in order to decide the MTF of paper. This method is also experimentally efficient since only one bar–target image needs to be measured. However, it is not easy to produce an ideal bar–target image having sufficiently sharp knife edges.

In this article, we propose a new simple method to measure the MTF of paper, and apply the measured MTF to analyze the dot gain effect in halftone print. In our method for measuring the MTF of paper, a pencil

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light distribution is projected to paper and the perfect specular reflector. The MTF of paper is calculated from the ratio between the two response images in spatial frequency domain. Since the spatial frequency characteristic of input pencil light can be obtained from the response of perfect specular reflector, it does not need to produce the input illuminant having "ideal" impulse characteristic. Next, we predict the reflectance distribution of halftone print using the MTF of paper in microscopy in order to analyze the dot gain effect caused by the light scattering in paper since the dot gain effect can clearly be observed in halftone micro-structure. Finally, a simulation is carried out to remove the light scattering effect from the predicted image. Since the simulated image is not affected by the optical dot gain, it can be applied to analyze the real dot coverage.

2. A simple method to measure MTF of paper using perfect specular reflector

2.1 Methodology

A simple method is proposed to measure the MTF of paper. A pencil light profile is projected to paper and the intensity distribution of reflected light, $o_l(x,y)$ at spatial coordinate (x,y), is measured. The light transfer behavior of the pencil light into paper is given by,

$$o_l(x,y) = i_l(x,y) * \{r_p \mathrm{PSF}_p(x,y)\}\,, \tag{1}$$

where $i_l(x,y)$ is the intensity distribution of incident pencil light, r_p is the reflectance of paper, $\mathrm{PSF}_p(x,y)$ is the PSF of paper and $*$ indicates the operation of convolution integral. From the Fourier transform of Eq. (1), the MTF of paper is given by

$$\mathrm{MTF}_p(u,v) = \frac{1}{r_p}\frac{|O_l(u,v)|}{|I_l(u,v)|} \quad \text{at} \ \ (u,v) : |I_l(u,v)| > e_{th}, \tag{2}$$

where $O_l(u,v)$ and $I_l(u,v)$ are the Fourier transformations of $o_l(x,y)$ and $i_l(x,y)$, respectively. Theoretically, the MTF of paper can be calculated at any (u,v) where $|I_l(u,v)| > 0$ using Eq. (2). However, the signal-to-noise ratio becomes to be worse when $|I_l(u,v)|$ is small value. The empirical threshold value e_{th} is introduced to cutoff the MTF whose accuracy of calculation is low. Equation (2) indicates that the MTF of paper can be calculated if $I_l(u,v)$ and r_p are obtained. If the function $i_l(x,y)$ can be assumed as ideal impulse, i.e. two dimensional Dirac delta $\delta(x,y)$ defined by

$$\delta(x,y) = 0 \qquad \text{if} \quad (x,y) \neq (0,0)$$

and

$$\iint_{-\infty}^{\infty} \delta(x,y)\, dxdy = 1,$$

the function $I_l(u,v)$ becomes to be one at any spatial frequency (u,v). However, the function $I_l(u,v)$ practically decreases in high spatial frequency in many cases since it is hard to produce the ideal impulse illuminant. To solve this problem, in our method, the same illuminant $i_l(x,y)$ is projected to a perfect specular reflector in order to obtain the exact distribution of $I_l(u,v)$, and the intensity of reflected light $o'_l(x,y)$ is measured, where we assume that the reflectance of the perfect specular reflector are 1 and its PSF can be represented as two dimensional Dirac delta, respectively. Hence $o'_l(x,y)$ is the same as $i_l(x,y)$. The function $I_l(u,v)$ can be calculated from the Fourier transformation of $o'_l(x,y)$. Finally, the reflectance of paper r_p is decided by following equation using the definition that $\mathrm{MTF}_p(0,0) = 1$ in Eq. (2):

$$r_p = \left|\frac{O_l(0,0)}{I_l(0,0)}\right|. \tag{3}$$

2.2 Experimental system

An optical microscope (BX50, Olympus) was used for measuring $o_l(x,y)$ and $o'_l(x,y)$. This microscope illustrated in Fig. 1 has two halogen light sources which illuminate the sample from the front side (reflectance mode) and the back side (transmittance mode), respectively. In this measurement, the reflectance mode is used. The intensity distribution of pencil light $i_l(x,y)$ is produced by closing iris and narrowing down the light beam. A plastic plate coated with chrome and polished is used as the perfect specular reflector. The reflected lights, $o_l(x,y)$ and $o'_l(x,y)$, are exposed with a digital monochrome camera (INFINITY4-11M, Lumenera corp., CCD, USB2.0) attached to the microscope which each pixel has 12-bit depth, maximum resolution is 4008×2672, and the sampling pitch on the captured image is 0.67μm. To convert the light source to white color, two Light Blue Daylight (LBD) filters

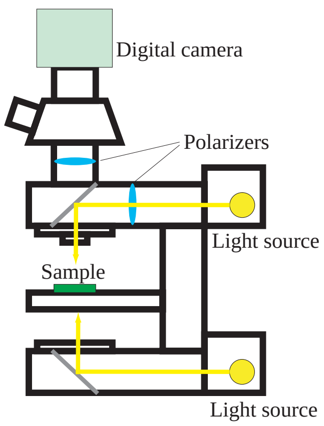


Fig. 1 The optical microscope having two light sources for reflectance and transmittance measurements

were placed in front of each light source. To eliminate the specular reflection component, two polarizers were placed in front of the light source for reflectance mode and the camera, respectively. For spectroscopy analysis, a bandpass filter can be placed in front of the camera. We arranged five types of bandpass filter whose peak wavelengths of spectral transmittance are 450, 500, 530, 550 and 600nm, respectively. When $o'_l(x, y)$ from the perfect specular reflector is measured, the polarizer in front of the camera was detached.

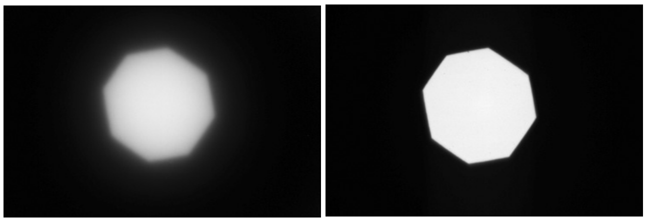
2.3 Measuring result of paper's MTF

We measured the MTF of an inkjet printing paper (XP–101, Canon) having a coating of gloss. Figures 2(a) and (b) show measured images $o_l(x, y)$ (paper) and $o'_l(x, y)$ (perfect specular reflector), respectively. Compared to $o'_l(x, y)$, the image $o_l(x, y)$ is significantly blurred by the MTF of paper. Calculating the MTF in Eq. (2), the threshold value e_{th} was set to 0.020 empirically. Figure 3 shows a three-dimensional plot of measured $\mathrm{MTF}_p(u, v)$ with 550nm bandpass filter. Figure 4 shows two-dimensional plots of this MTF with respect to several deflection angles on the polar coordinate. It shows the MTF of this paper is isotropic. The solid line in Fig. 4 indicates an empirically-determined approximation curve by an equation

$$\mathrm{MTF}_p(f) \approx \frac{1}{\sqrt{1 + (2\pi f d)^2}}, \tag{4}$$

where f is the spatial frequency and d is a fitting coefficient; in this case $d = 0.0106$. Equation (4) is a square root of Lorentzian. Rogers also fitted the data of paper's MTF with the same equation [8]. Inoue *et al.* fit their data with a function $[1 + (2\pi f d)^2]^{-3/2}$ [2]. This function is a little different from Eq. (4), however, Rogers represents Eq. (4) would actually give a better fit to their data, too. These discussions confirm high measurement accuracy of our data. Figure 5 shows MTFs with each bandpass filter. The shorter the peak wavelength of bandpass filter is, the higher the MTF is. Photons having short wavelength cannot penetrate into deep point of paper since its scattering power is strong, therefore, the MTF becomes to be high. However the difference is not significant. Figure 6 shows the measured MTFs of other types of paper for the offset printing such as a gloss–coated, a semi–gloss–coated, a matte–coated and a uncoated produced by MITSUBISHI PAPER MILLS LIMITED. The coated types of paper have higher MTF than the uncoated paper except for the inkjet printing paper. The inkjet printing paper has lower MTF than all types of offset printing paper. We consider that the inkjet printing paper has a high scattering of light since it has a porous structure in coating layer in order to increase the penetrating ability of ink into paper.

Four principal advantages of our method and system are (1) simplicity: only two images, $o_l(x, y)$ and $o'_l(x, y)$, need to be measured, (2) high accuracy: the same approximation can be done to the measured data with the conventional MTF model, (3) orientational dependency can be analyzed with Fig. 3 and (4) wavelength dependency can be analyzed with Fig. 5.



(a) $o_l(x, y)$ (b) $o'_l(x, y)$ $(= i_l(x, y))$

Fig. 2 The reflection images of pencil light from (a) the gloss–coated inkjet printing paper and (b) the perfect specular reflector

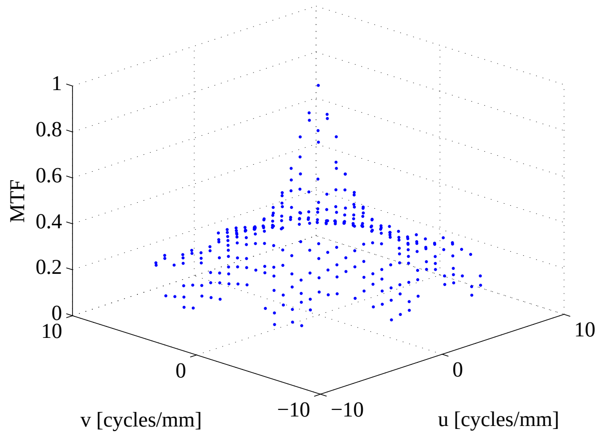


Fig. 3 A three-dimensional plot of measured paper's $\mathrm{MTF}_p(u, v)$ with 550nm-bandpass filter

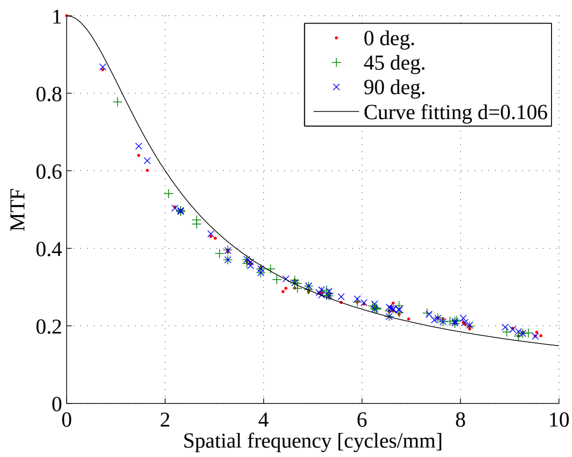


Fig. 4 Two-dimensional plots of $\mathrm{MTF}_p(u, v)$ with respect to several deflection angles on the polar coordinate

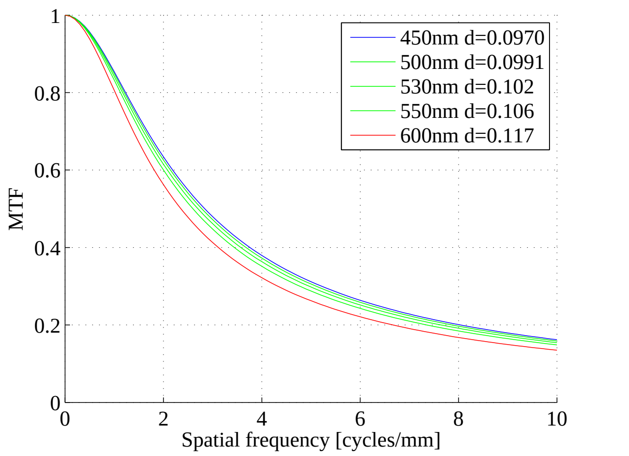


Fig. 5 Measured MTFs of the inkjet printing paper $\mathrm{MTF}_p(u, v)$ with several bandpass filters (Approximated curves using Eq. (4))

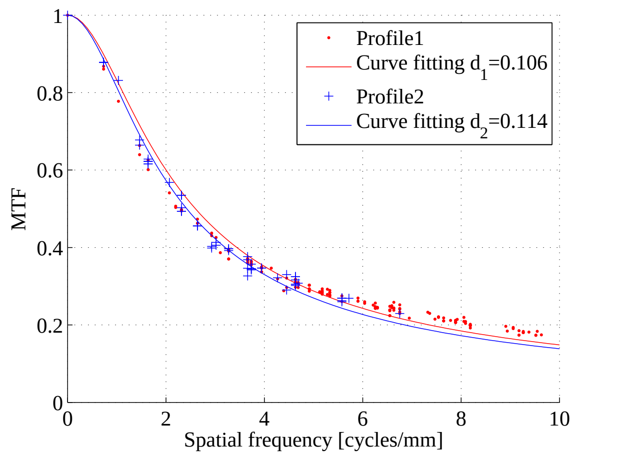


Fig. 7 The differece of measured MTF when the different diameter was used: 1mm (profile1) and 1.4mm (profile2)

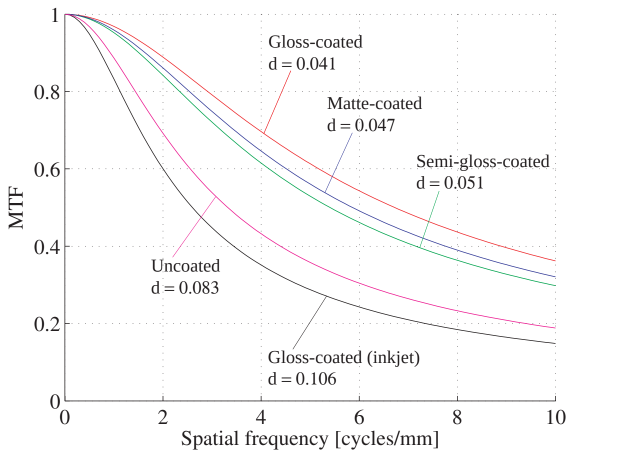


Fig. 6 Comparing MTFs of various types of paper: an inkjet printing paper and four types of offset printing paper which are gloss–coated, semi–gloss–coated, matte–coated and uncoated

2.4 Independency of MTF on projection profile

The proposed method in the sub–section 2.1 measures the projection profile $i_l(x, y)$ and its effect is canceled in Eq. (2). Therefore, theoretically, the measured MTF is independent on the projection profile. However, practically, if the function $I_l(u, v)$ has small values at the spatial frequency (u, v), the signal–to–noise ratio of $\mathrm{MTF}_p(u, v)$ becomes to be low. Therefore, accurate MTF can be measured by the projection profile which has the enough high spatial frequency components. In other words, the projected illuminant should be the profile which has

1. a small diameter, or
2. parts of sharp edge.

The profile illustrated in Fig. 2(b) has not so small diameter which is about 1mm, however, it has several parts of sharp edge. Since our microscope system can change the diameter of projection profile, we measured and investigated the dependency of MTF on the projection profile (diameter). Figure 7 shows the difference of measured MTF when the different diameter was used. In Fig. 7, the profile1 indicates the measurement result of Fig. 2(b), and the profile2 has bigger diameter than the profile1, which is about 1.4mm. Compared to the profile1, the MTF measured by the profile2 has less data points since its signal–to–noise ratio is lower and many data points are cut off by the threshold e_{th} in Eq. (2).

3. Reflectance distribution prediction of printed image in microscopy

We proposed a simple method to measure the MTF of paper in previous section. In this section, we predict the reflectance distribution of halftone print using the measured MTF in microscopy in order to analyze the dot gain effect. Several models have been proposed to describe the light propagation in printed paper. As macroscopic prediction models which predict the average reflectance of printed halftone patch, two of the most popular models are the Murry-Davis equation and the Yule-Nielsen equation [4], [5]. The Murry-Davis equation predicts the reflectance by the dot coverage of print, however, the prediction accuracy is not well since it does not consider the dot gain effect. The Yule-Nielsen equation modifies the Murry-Davis equation considering the dot gain effect with the empirical factor n. The Clapper-Yule model [9] considers explicitly into account both the multiple internal reflections between the paper substrate and the print-air interface and the lateral propagation of light within the paper bulk. Hersch *et al.* [10] and Hébert *et al.* [11]–[13] propose their models modifing the Clapper-Yule model.

Yang *et al.* [14] propose their model considering the effect of ink penetration into paper substrate. However, these models can only predict the average reflectance in macroscopy. As microscopic prediction model, Inoue *et al.* propose the reflection image model [3]. We introduce the reflection image model in this article since the dot gain effect can clearly be observed in the halftone micro-structure.

3.1 Prediction by reflection image model

In the reflection image model illustrated in Fig. 8, the light transfer behavior in halftone print is given by

$$o_{rh}(x,y) = i_r r_s + i_r(1-r_s)r_p\{t_i(x,y) * \mathrm{PSF}_p(x,y)\}t_i(x,y), \quad (5)$$

where $o_{rh}(x,y)$ is the output intensity distribution when the spatial uniform light i_r is illuminated to a halftone print, and r_s is the specular reflectance of the print. The specular reflectance r_s is determined by the relative refractive index between air and the printed paper. To be exact, the specular reflectance r_s should be the function of the spatial coordinate (x,y) since the refractive index of paper and that of ink are different. However, since the difference of refractive indexes between paper and ink is enough smaller than the difference between air and paper or air and ink, it can be assumed that r_s is spatially uniform. Hersch *et al.* describe and use the same assumption in their work [10]. In Eq. (5), a portion of i_r is reflected by the specular reflectance r_s of the print. The other portion of incidence, $i_r(1-r_s)$, transmits the ink layer having its transmittance distribution $t_i(x,y)$. The transmitted light from the ink layer is scattered by the PSF of paper, $\mathrm{PSF}_p(x,y)$, and reflected by the reflectance of paper, r_p. The reflected light from the paper layer is observed after transmitting the ink layer having $t_i(x,y)$ again. The specular reflectance r_s is not concidered, i.e. $r_s = 0$, in the original model described in Ref. [3]. However it is difficult to perfectly exclude the specular reflection component even if the polarization technique is used like our microscope system, therefore, we consider r_s. If $t_i(x,y) = 1$ at any position (x,y) in Eq. (5), it indicates there is no ink layer. Therefore, the output light intensity o_{rp} from un-printed paper is given by

$$o_{rp} = i_r r_s + i_r(1-r_s)r_p. \quad (6)$$

A relative reflectance distribution of printed paper $r_i(x,y)$ from un-printed paper is defined by

$$\begin{aligned} &r_i(x,y) \\ &= o_{rh}(x,y)/o_{rp} \\ &= (1-A) + A\{t_i(x,y) * \mathrm{PSF}_p(x,y)\}\,t_i(x,y) \end{aligned} \quad (7)$$

with

$$A = \frac{(1-r_s)r_p}{(1-r_s)r_p + r_s}. \quad (8)$$

If the PSF of paper is symmetric i.e. it has no phase shift, the convolution integral part in Eq. (7) can be easily calculated using the MTF of paper and Fourier transform:

$$t_i(x,y) * \mathrm{PSF}_p(x,y) = \mathfrak{F}^{-1}\{\mathfrak{F}\{t_i(x,y)\}\mathrm{MTF}_p(u,v)\}, \quad (9)$$

where $\mathfrak{F}\{\}$ and $\mathfrak{F}^{-1}\{\}$ are the operations of Fourier transform and inverse Fourier transform, respectively. The function $r_i(x,y)$ is obtainable since $o_{rh}(x,y)$ and o_{rp} are measurable with our microscope system in reflectance mode. The reflectance distribution can be predicted using the right-hand side of Eq. (7) if $t_i(x,y)$ and A are obtained. To obtain $t_i(x,y)$, the intensity distribution of halftone print, $o_{th}(x,y)$, is measured with the transmittance mode of our microscope system. The intensity distribution $o_{th}(x,y)$ is given by

$$o_{th}(x,y) = i_t t_p t_i(x,y), \quad (10)$$

where i_t is the light intensity of illuminant for transmittance mode and t_p is the transmittance of paper. The incident light transmits the paper layer and ink layer, respectively (Fig. 8). The incident light is scattered in paper when it transmits the paper layer. However, the convolution integral by the PSF of paper can be ignored mathematically since spatial uniformities of i_t and t_p are assumed. Equation (10) is called the transparency image model [15]. The intensity distribution of un-printed paper, $o_{tp}(x,y)$, is also measured with the transmittance mode of our microscope system. The intensity distribution o_{tp} is given by

$$o_{tp} = i_t t_p. \quad (11)$$

From Eqs. (10) and (11), one can derive

$$t_i(x,y) = \frac{o_{th}(x,y)}{o_{tp}(x,y)}. \quad (12)$$

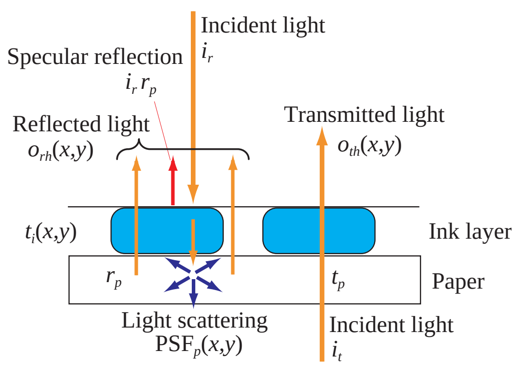


Fig. 8 The light transfer behaviors of the reflection image model and the transparency image model

The coefficient A can be obtained from the measurement of solid print. The solid print has 100% dot coverage, therefore $t_i(x,y) = t_{i,100}$ ($t_{i,100}$: constant value). Since $t_{i,100}$ is constant, the convolution integral by $\mathrm{PSF}_p(x,y)$ can be mathematically ignored in Eq. (7):

$$r_{i,100} = (1-A) + A\left\{t_{i,100}\right\}^2, \tag{13}$$

where $r_{i,100}$ is $r_i(x,y)$ when $t_i(x,y) = t_{i,100}$. Therefore, one can derive

$$A = \frac{r_{i,100}-1}{\left\{t_{i,100}\right\}^2 - 1}, \tag{14}$$

where $r_{i,100}$ can be obtained from the fraction between Eqs. (5) and (6), and $t_{i,100}$ can be obtained from Eq. (12). The accuracy of prediction can be evaluated using the error distribution $e(x,y)$ between the measured function $r_i(x,y)$ and the predicted function $r'_i(x,y)$ by the right-hand side of Eq. (7):

$$e(x,y) = |r_i(x,y) - r'_i(x,y)|, \tag{15}$$

or can be evaluated by the difference d_{ave} between the average reflectance of measured and predicted:

$$d_{ave} = r_{ave} - r'_{ave} \tag{16}$$

with

$$r_{ave} = \frac{1}{l_x l_y}\int_0^{l_y}\int_0^{l_x} r(x,y)dxdy$$
$$r'_{ave} = \frac{1}{l_x l_y}\int_0^{l_y}\int_0^{l_x} r'(x,y)dxdy,$$

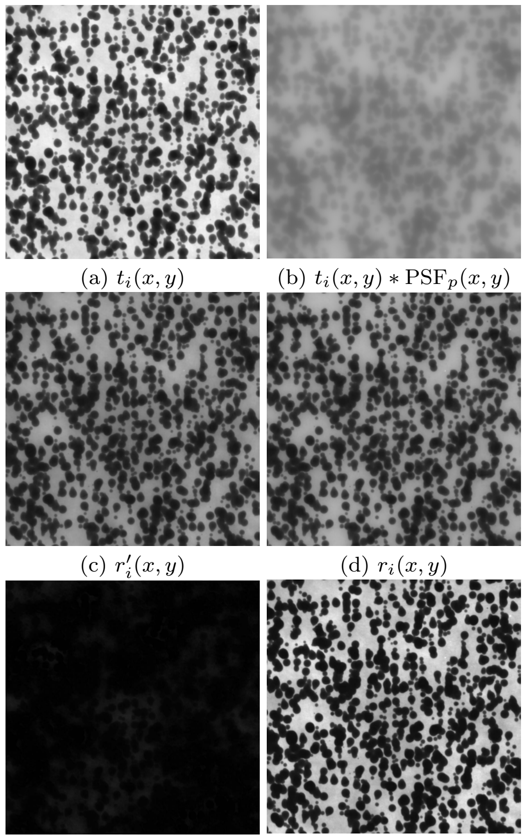
where l_x and l_y are the horizontal length and the vertical length of both $r(x,y)$ and $r'(x,y)$.

3.2 Prediction experiment

Using Eq. (7), the prediction experiment of reflectance distribution was performed. A dye-based inkjet printer (W2200, CANON) was used. The printing resolution is 1200dpi. We printed 11 halftone color patches using cyan ink whose each nominal dot coverage is 0 (un–print), 10, 20, ..., 90 and 100% (solid print), respectively. The gloss–coated inkjet printing paper whose MTF was measured in Section 2 was used. First, we measured the un-printed paper with the microscope in the reflectance mode and the transmittance mode to obtain o_{rp} and o_{tp}. Next, we measured the solid print and obtained $r_{i,100}$ and $t_{i,100}$ to calculate the value A by Eq. (14). Next, we measured each halftone print to obtain each $o_{rh}(x,y)$ and $o_{th}(x,y)$. Next, $r_i(x,y)$ and $t_i(x,y)$ of each halftone print were calculated by Eqs. (7) and (12). Next, the predicted reflectance distribution $r'_i(x,y)$ of each halftone print was calculated by the right-hand side of Eq. (7). Finally, $e(x,y)$ and d_{ave} were calculated by Eqs. (15) and (16). Figures 9(a)-9(e) show the measured or predicted images of $t_i(x,y)$, $t_i(x,y) * \mathrm{PSF}_p(x,y)$, $r'_i(x,y)$, $r_i(x,y)$ and $e(x,y)$. Figure 10(a) shows the average reflectance, r_{ave} and r'_{ave} with respect to each input nominal dot coverage. At the all points, the predicted value is less than or equal to the measured value. It means the prediction would overestimate the optical dot gain effect. We consider that, to be exact, the penetration of ink into paper a little decreases the scattering ability of paper layer. However, the prediction accuracy is relatively well since d_{ave} was 0.0216 in the worst case.

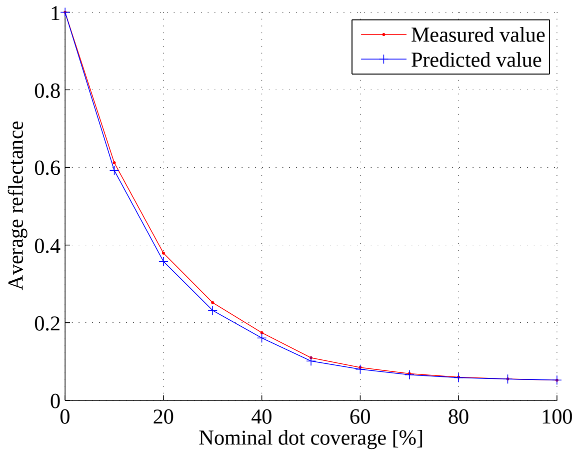
3.3 Prediction for pigment-based print

To analyze the dependence of prediction accuracy on the type of ink, the same prediction experiment as described in sub–section 3.2 was performed with respect to the pigment–based print. Several patches printed with pigment–based offset printer was used, whose nominal dot coverage are 0 (un–print), 10, 20, 40, 70 and 100% (solid print) of cyan ink, respectively.

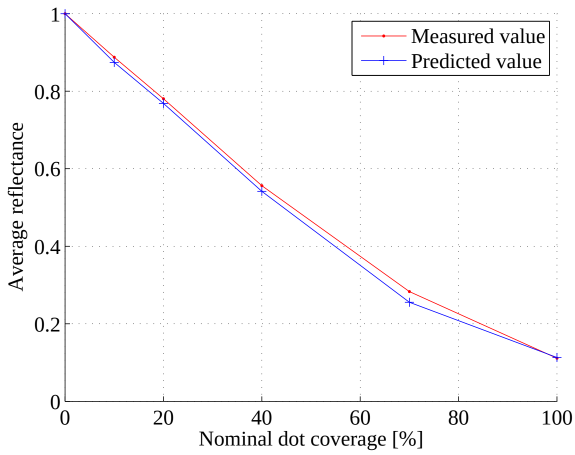


(a) $t_i(x,y)$ (b) $t_i(x,y) * \mathrm{PSF}_p(x,y)$ (c) $r'_i(x,y)$ (d) $r_i(x,y)$ (e) $e(x,y)$ (f) $r''_i(x,y)$

Fig. 9 Measured and predicted images: (a) the measured transmittance distribution, (b) the transmittance distribution convoluted by the PSF of paper (c) the predicted reflectance distribution, (d) the measured reflectance distribution, (e) the error distribution between the measured and predicted, and (f) the simulated reflectance distribution without the optical dot gain



(a)



(b)

Fig. 10 The average reflectance with respect to the nominal dot coverage: (a) the dye-based inkjet print and (b) the pigment-based offset print

Figure 10(b) shows the average reflectance of measured (r_{ave}) and predicted (r'_{ave}). Compared to the dye–based print, the prediction accuracy was lower since the maximum error was 0.0275. We consider that, in the reflection image model, the light scattering effect in ink layer is ignored, however, the scattering in pigment is bigger than in dye, therefore, the prediction accuracy of pigment–based print was a little lower than that of dye–based print. If the ink layer has high scattering ability, the incident ratio into paper layer becomes to be lower. Therefore, we consider that the optical dot gain in the pigment–based print is also lower than that of dye–based print. If the ink layer has high scattering ability, the incident ratio into paper layer becomes to be lower. Therefore, we consider that the optical dot gain in the pigment–based print is also lower than that of dye–based print.

3.4 Dot gain analysis

The dot gain effect can be categorized to two types: a mechanical dot gain and an optical dot gain. The mechanical dot gain is a phenomenon in printing whereby printed dots are actually printed bigger than intended because of the viscosity of ink. The optical dot gain is a phenomenon in printing whereby printed dots are perceived bigger than intended because of the light scattering in paper. It is difficult to separate two types of dot gain since these are observed simultaneously. In this sub-section, we try to separate two types of dot gain. In Eq. (7), we can consider that the mechanical dot gain effect is included in $t_i(x, y)$, and on the other hand, the optical dot gain effect is caused by $\mathrm{PSF}_p(x, y)$. Therefore, the function $r_i(x, y)$ includes both effects of mechanical dot gain and optical dot gain. If we set $\mathrm{MTF}_p(u, v) = 1$ in Eq. (9), predicted $r_i(x, y)$ would not contain the optical dot gain. Figure 9(f) shows the simulated image $r''(x, y)$ where $\mathrm{MTF}_p(u, v)$ is set to one. Compared to the $r'(x, y)$ (Fig. 9(c)), the image $r''(x, y)$ is brighter and sharper because of no optical dot gain. The image $r''(x, y)$ has only the effect of mechanical dot gain, therefore, it can be applied to determine the real dot coverage of print.

4. Conclusion

A new method to measure the MTF of paper was proposed. Our method is experimentally efficient since required measurements to calculate the MTF are only two images: reflection images of a pencil light from paper and from a perfect specular reflector. Our method would have high measurement accuracy since the measured data can be approximated by the same function suggested by Rogers [8]. Using the measured MTF, the microscopic reflectance distribution of inkjet image was predicted by the reflection image model. The prediction accuracy of average reflectance was less than 3%. A simulation was done to remove the effect of optical dot gain from the predicted reflectance distribution changing the MTF of paper to one. The simulated image has only the effect of mechanical dot gain, and can be applied to analyze the real the dot coverage of printed image.

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