Journal of Imaging Science and Technology® 51(2): 127–140, 2007.

Modulation Transfer Function Measurement for Ink Jet Printed Silk Fabrics

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Abstract. *The modulation transfer function (MTF) is a standard method used for estimating the image quality of a component for detail recording in an image forming system and for printing quality of the final products. This study focused on the measurement of MTF of nonprinted and printed silk fabrics and a correlation of the MTF data to sharpness of the printed silk fabric using the in-house formulated ink jet ink. The MTF of the surface was measured using the sinusoidal test pattern in contact with the fabric using spatial frequencies from 0.375 to 3.0 cycles/mm. The sinusoidal test target scanned by a microdensitometer in the reflection density mode. These data comprise two frequencies; the high frequency is the characteristic of the fabric while the low frequency is the light scattering of the yarns in contact with the sinusoidal target. The sinusoidal curves at the low frequency were used for further calculation of the MTF values. The result indicated that the measurement of MTF of silk fabric using the contact sinusoidal method can find the point spread function of silk fabrics. This research investigated the relationships of weave style and direction, wicking properties, and the MTF of four different silk fabrics with plain weave (silk A, C, and D) or twill weave (silk B). Dot gain by the Yule–Nielsen model was investigated. The coefficient d calculated by the MTF empirical model was 0.0604 and the coefficient n by the Yule–Nielsen model was 1.636 for silk D which had the lowest d and n coefficients compared with other silk fabrics, indicating good quality in terms of image sharpness. © 2007 Society for Imaging Science and Technology.*
[DOI: 10.2352/J.ImagingSci.Technol.(2007)51:2(127)]

INTRODUCTION

Ink jet printing is becoming an important technology in printing textiles. It has the potential to shorten the lead time from design to production, speed up production of samples, and reduce production lot size and, hence, inventory cost. Ink jet printing can be defined as the application of a fluid control device with specific fluid control parameters. Microscopic ink drops are emitted under pressure from an orifice onto a medium for a halftone image. The size of an orifice can vary from 10 to about 100 μm depending on the technology used.

In general, print quality is determined by its sharpness, graininess, tone reproduction, and color reproduction characteristics. Furthermore, printing quality in ink jet printing is strongly dependent on the interactions between the ink and media. In ink jet printing on paper, the significance of ink-media interactions has been recognized and researched.[1,2]

Ink jet printing on textiles, however, is a different matter. The impact of an ink onto the fibrous structure of a textile is a difficult issue; a true understanding of ink-fabric interactions and their effects on print quality was rarely achieved in the literature. In previous studies, techniques for measuring the modulation transfer function (MTF) of paper have been studied.[3–9] Paper is a well-known opaque medium similar to textile. In both, incident light entering the medium causes absorption, transmission, reflection, and scattering. The light scattering phenomena can be represented by the point spread function (PSF).[10–13] This phenomenon produces optical dot gain and has a significant influence on image quality, particularly tone reproduction, characteristics of halftone printing, and digital halftone imaging. If the light scattering within a textile is assumed isotropic, it can be specified either by the PSF, the line spread function,[13] or the MTF in the spatial frequency domain.

In this research, we propose a method for measuring MTF for nonprinted and printed silk fabrics using a sinusoidal test pattern contact method.[8,9,14] The dot gain effect according to the Yule–Nielsen model[11] was used to confirm the MTF technique.

EXPERIMENT

Materials

The silk fabrics used in this study were obtained from Thai Silk Company Limited. Four degummed and nonbleached silk fabrics were washed with light soap solution (SDC, ISO

Received Dec. 14, 2006; accepted for publication Dec. 27, 2006.
1062-3701/2007/51(2)/127/14/$20.00.

Table I. Description of the silk fabrics.

Type	Style	Yarn No. (denier, warp×weft)	No. of yarn per unit length (in.) (warp×weft)
A	Plain	104×87	130×51
B	Twill	102×66	140×51
C	Plain	79×67	130×70
D	Plain	98×84	130×51

105), then cleansed with water, and dried in an ambient atmosphere. The description of silk fabrics is presented in Table I. All are plain style silk fabrics except B, a twill style.

Fabric Wicking Behavior Measurement

Wicking of silk fabrics was evaluated using the INDA IST 10.0-70 method 10.3 for nonwoven fabrics. Two sets of the fabric samples 25 mm wide and 305 mm long were prepared. One set of the samples was cut in the warp direction and the other in the weft direction. During the test, each fabric strip was positioned vertically over a glass beaker containing one of several fluids, and one end of the fabric was immersed in the fluid for 5 min. The measurements were conducted using both distilled water and 2-octanol. The ratio between the measurements of water and 2-octanol on the textile fabric was described as the wicking ratio (water/2-octanol) and was used as an indicator of the absorption nature, surface hydrophilicity, and estimated pore sizes of the silk fabrics.

Ink Jet Ink

The ink components were weighed to produce a mix in which the deionized water, diethylene glycol, glycerol, urea, and colorant were present in the following relative concentrations: Dye 5.0, diethylene glycol 10.0, glycerol 10.0, urea 5.0, and deionized water 70.0 percent by weight. Four colors from Orient Chemical Industries, Osaka, Japan comprising cyan (Water Blue 9, C.I. Acid Blue 9, of the triphenylmethane class); magenta (Water Red 27, C.I. Acid Red 52, of the xanthene class); yellow (Water Yellow 1, C.I. Acid Yellow 23, of the monoazo class); and black (Water Black R510, C.I. Acid Black 2, of the azine class) were used for the preparation of four ink jet inks. The mixture was then stirred at 100 rpm until a homogeneous solution was obtained. Then acetic acid was added to control the ink *p*H in a range of 5.2–6.2. The inks were later filtered through a 400 mesh nylon screen to eliminate dust and foreign particles and prevent clogging problems. Then the inks were stored in a vaccum desiccator, which was connected to a suction pump to remove air bubbles under reduced pressure. The four colors of ink jet ink were each poured into the ink tanks for a Canon ink jet printer. The ink jet viscosity was investigated using a spindle No. 31 in a Brookfield viscometer (model DVIII) at an ambient temperature, and a shear rate of 250 s^{-1}.

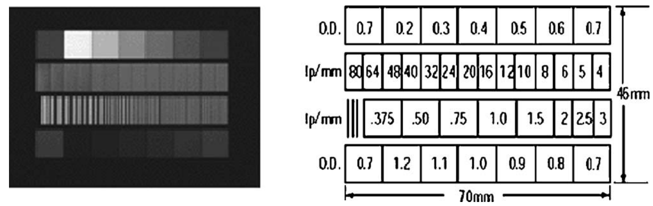


Figure 1. Sinusoidal type transmittance target from Edmund Optical®.

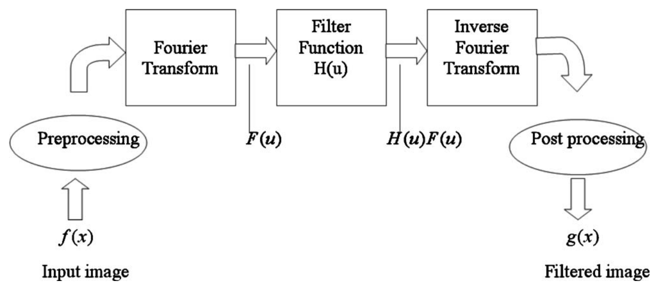


Figure 2. Frequency domain filtering operations.

Fabric Preparation

Four degummed and nonbleached silk fabrics were washed with soap solution (SDC, ISO 105), then cleansed with water, and dried in an ambient atmosphere. To print on a flexible textile substrate, it is necessary to assure a smooth transportation of a stable dimension of the fabric into the printer feed rollers. Any deformation of the fabric had to be prevented. To ensure printing quality, the fabric sample was held on a piece of A-4 office printing plastic sheet with conventional adhesive tape. The printed fabrics were then steamed at 80 °C for 5 min and 110 °C for 2 min to fix the printed colors.

Measuring MTF of Silk Fabrics

A sinusoidal test pattern contact method was used in this research. The sinusoidal glass test pattern used was NT54-803 from Edmund Optical®, where a variable transmission type pattern made on exceptionally high resolution film was sandwiched in soda lime glass (Fig. 1). The sinusoidal test pattern arrays used for each sample silk fabric have spatial frequencies of 0.375, 0.5, 0.75, 1.0, 1.5, 2.0, 2.5, and 3.0 cycles/mm. It was placed in contact with the sample silk fabric and its reflection density distribution was measured with a microdensitometer (Konica, PDM-7, Tokyo, Japan). The measurement was made in the warp direction. The data was recorded as a reflection density and reflectance could then be obtained by Eq. (1),

$$R_o = 10^{-D_r}, \qquad (1)$$

where R_o is reflectance and D_r is reflection density. This reflectance corresponded to one dimension intensity of the output sinusoidal image.

Since the measured reflectance included the texture of the silk fabric, filtering in Fourier domain was applied in order to eliminate the silk fabric frequency from the sinusoidal frequency. The filtering operation is shown in Fig. 2.

It has been demonstrated that the MTF can be calculated from the contrast transfer function (CTF) of a print.[3–9] Thus the MTF of silk can be computed from the CTF of print and vice versa, as

$$MTF_{silk}(\omega) = 2 \cdot CTF_{print}(\omega) - 1, \quad (2)$$

where ω denotes the spatial frequency, CTF of the print can be calculated by Eq. (3),

$$CTF_{print}(\omega) = c(\omega)/c(0), \quad (3)$$

where $c(\omega)$ is for contrast, which can be obtained by Eq. (4), and i_{max} and i_{min} denote the maximum and minimum intensities of the output

$$c(\omega) = i_{max} - i_{min}. \quad (4)$$

The measured MTF of silk can be fitted by an empirical model, which can be expressed by Eq. (5) as follows:

$$MTF_{(\varpi)} = \frac{1}{[1 + (2\pi d\varpi)^2]^{3/2}}. \quad (5)$$

The coefficient, d for a light scattering distance in the silk fabric[10] and its corresponding PSF[5,6] are shown in Eq. (6),

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

Measuring n Value from the Yule–Nielsen Effect

Lithographic film was prepared, which contained 0%, 5%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100% dot area. It was placed in contact with the silk fabric and its reflection density was measured with a densitometer (Gretag D200-II). The relationship between the percent dot area and density of film reproduced on the silk was obtained. The data expressed in a form of the reflection density can be used to calculate the n values from the Yule–Nielsen model as shown by Eq. (7),[15]

$$D = -n \log\{1 - A[1 - 10^{-D_s/n}]\}, \quad (7)$$

where n is the Yule–Nielsen value for fitting the data. D_s is the optical density of the solid area coverage, A which is weighted by the dot area coverage.

Characteristics of the Printed Silk Fabrics

The cyan, magenta, yellow, and black inks were printed on the silk fabrics using a BJF-8500, Canon printer (Canon Inc., Tokyo, Japan). The printer was calibrated according to the manufacturer's instruction. The MTF values were measured for the printed silk fabrics by the contact sinusoidal method similar to the MTF measurement on the nonprinted silk fabrics. Further measurements for the n values and dot gain values of the printed images by the Yule–Nielsen model were also carried out. The QAE test chart was also printed for the four silk fabrics[14] and the printed lines were analyzed.

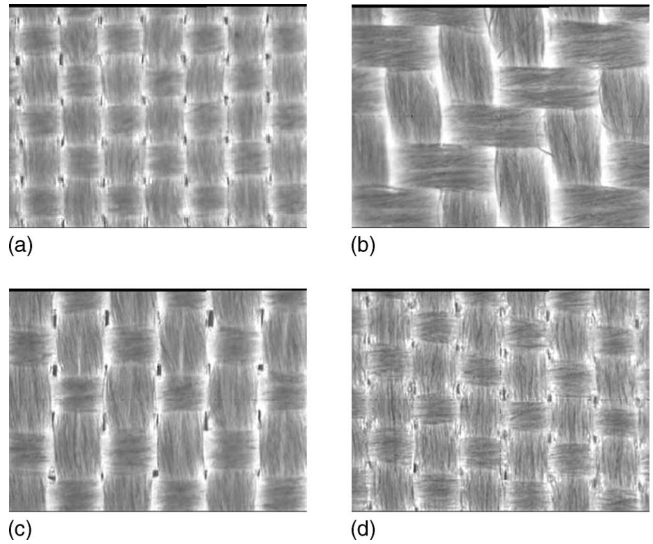


Figure 3. Morphological images of the silk fabrics: (a) silk type A, (b) silk type B, (c) silk type C, and (d) silk type D.

RESULTS AND DISCUSSION

Viscosity is the main characteristic of ink jet ink insofar as it is the prime driving parameter for the ink to pass through the nozzles and give acceptable print quality.[16] Ink jet printing may need to print more than one pass to achieve deeper shades because an ink jet printer creates tiny drops and ejects them to form images. To increase the dye concentration in the formulation is to eliminate the need for multiple-pass printing but it may affect the ink viscosity. In this study, the ink viscosity for each color was found to be cyan, 2.18 mPa s, magenta, 2.16 mPa s, yellow, 2.14 mPa s, and black, 2.34 mPa s, which conform to the standard range of requirement for ink jet ink and gave continuous and smooth printed images for all types of fabric.

Texture of Silk Fabrics

The texture and structure of the nonprinted silk fabrics observed in the transmission mode are shown in Fig. 3, and they were qualitatively analyzed for comparison as follows. The number of yarns per inch and their pore size are indicated in Table I and Fig. 3. The twill silk fabric (silk fabric B) has the smoothest surface structure because of the weave method. The twill weave fabrics, compared with the plain weave, have more pliable drape and hand, wrinkle resistance, resistance to collecting soil and soiling, durability, and are heavier, with a tendency to have defined face and back. Silk fabrics A, C, and D were studied for the effect of porosity. Silk fabric C, using low denier yarns and not having a high number of yarns per inch, has the largest pore size. Fabric B has a yarn floating twill structure and a high number of yarns per inch and yarn number, it has fewer pores and relatively smaller pore size. The area-to-pore size ratios of the silk fabrics A and D are nearly the same and higher than that of silk fabric C.

Figures 4–7 illustrate the analyzed reflection data by the fast Fourier transform (FFT) technique for the peaks at 0.375, 0.5, 0.75, 1.0, 1.5, 2.0, 2.5, and 3.0 cycles/mm for silks

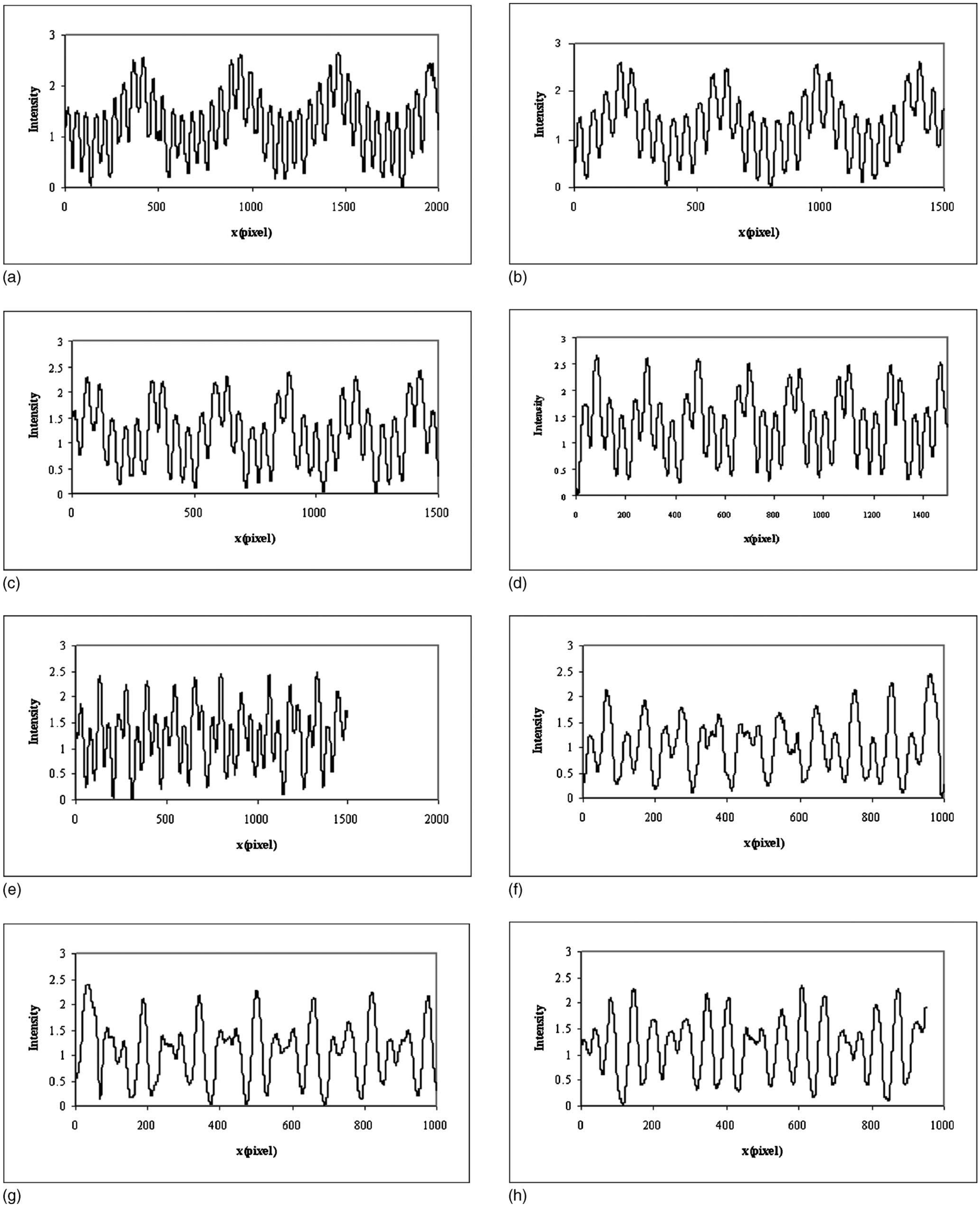


Figure 4. Microdensitometer traces for the sinusoidal test pattern contacted with silk fabric A at different applied spatial frequencies: (a) 0.375, (b) 0.5, (c) 0.75, (d) 1.0, (e) 1.5, (f) 2.0, (g) 2.5, and (h) 3.0 cycles/mm.

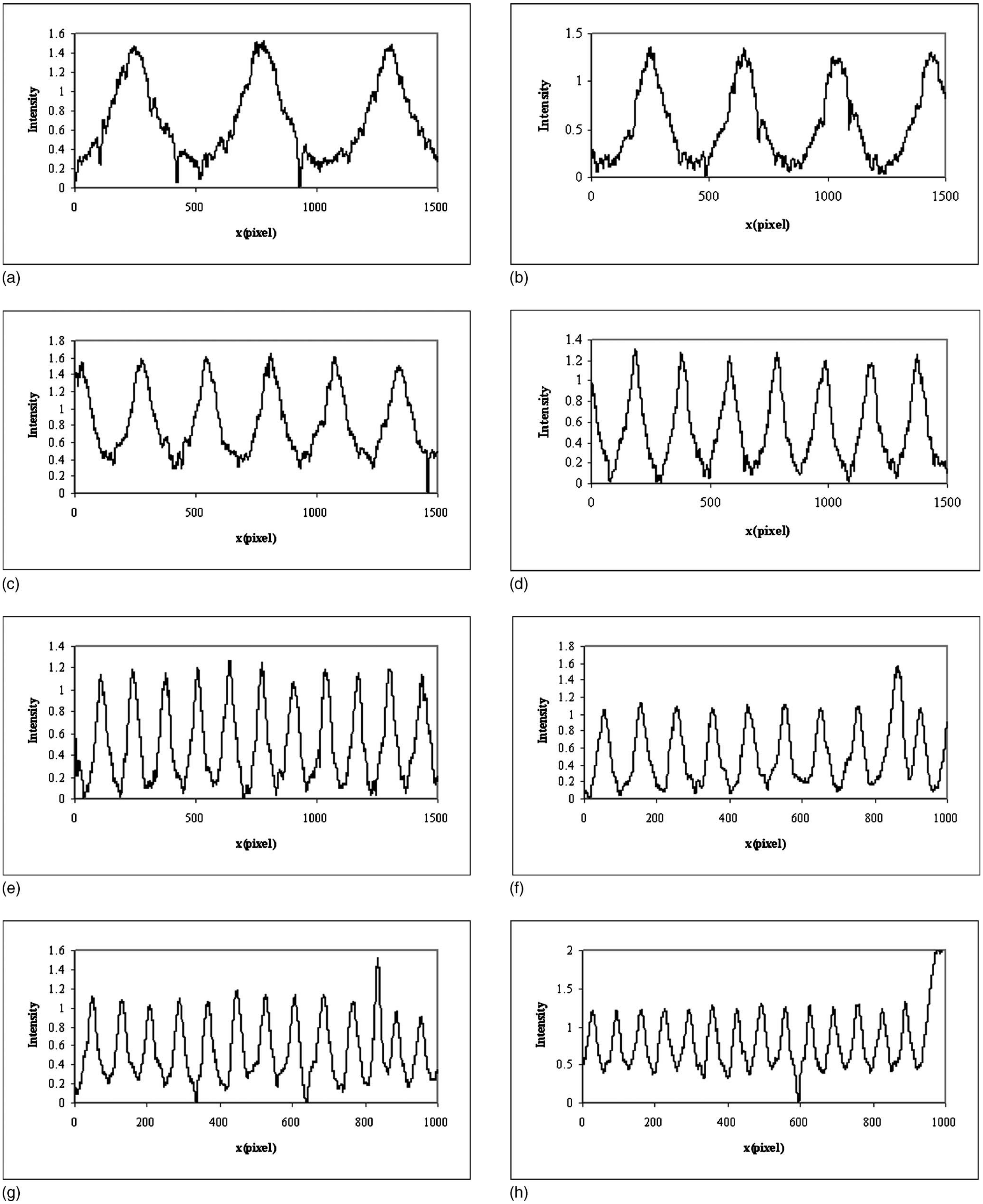


Figure 5. Microdensitometer traces for the sinusoidal test pattern contacted with silk fabric B at different applied spatial frequencies: (a) 0.375, (b) 0.5, (c) 0.75, (d) 1.0, (e) 1.5, (f) 2.0, (g) 2.5, and (h) 3.0 cycles/mm.

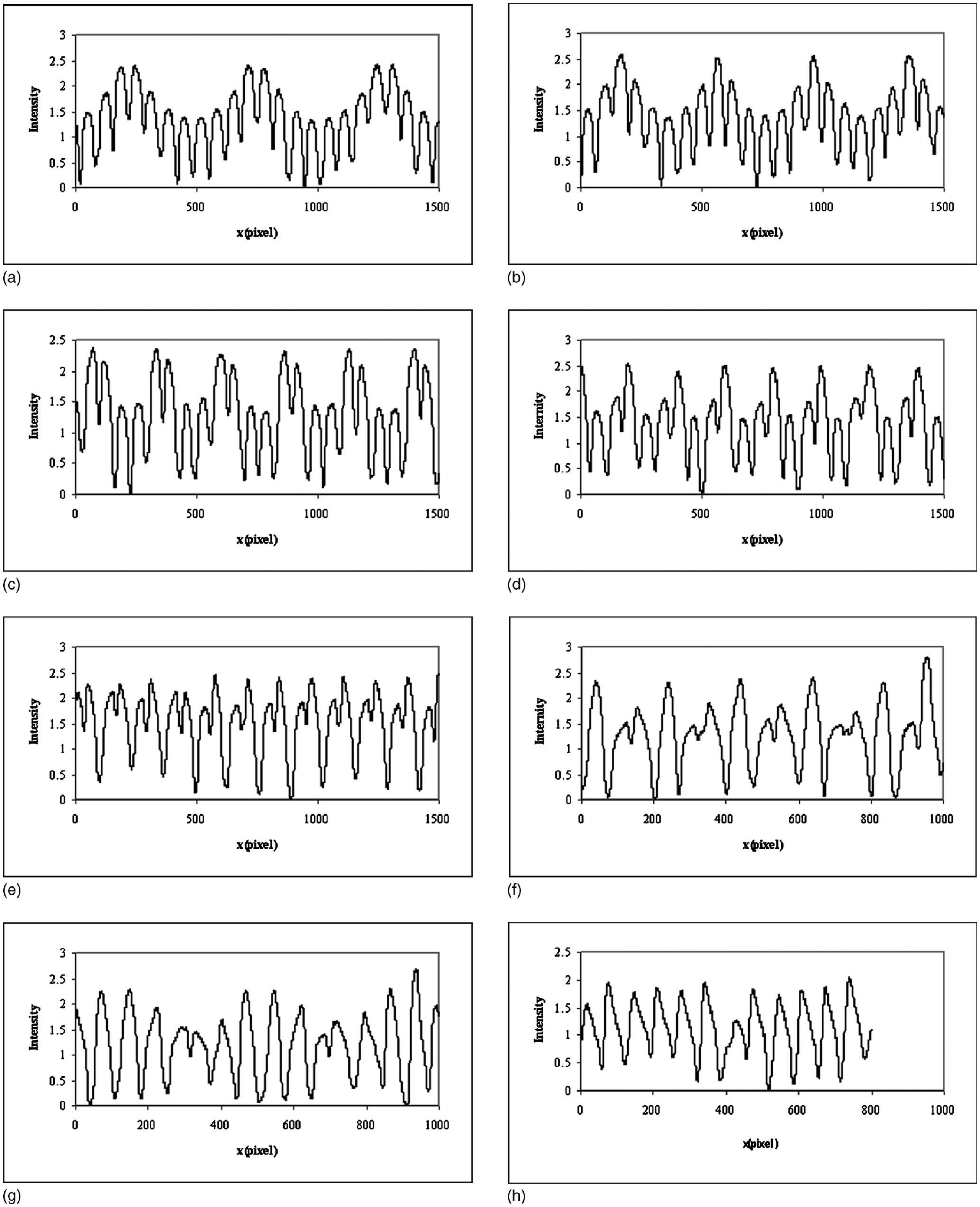


Figure 6. Microdensitometer traces for the sinusoidal test pattern contacted with silk fabric C at different applied spatial frequencies: (a) 0.375, (b) 0.5, (c) 0.75, (d) 1.0, (e) 1.5, (f) 2.0, (g) 2.5, and (h) 3.0 cycles/mm.

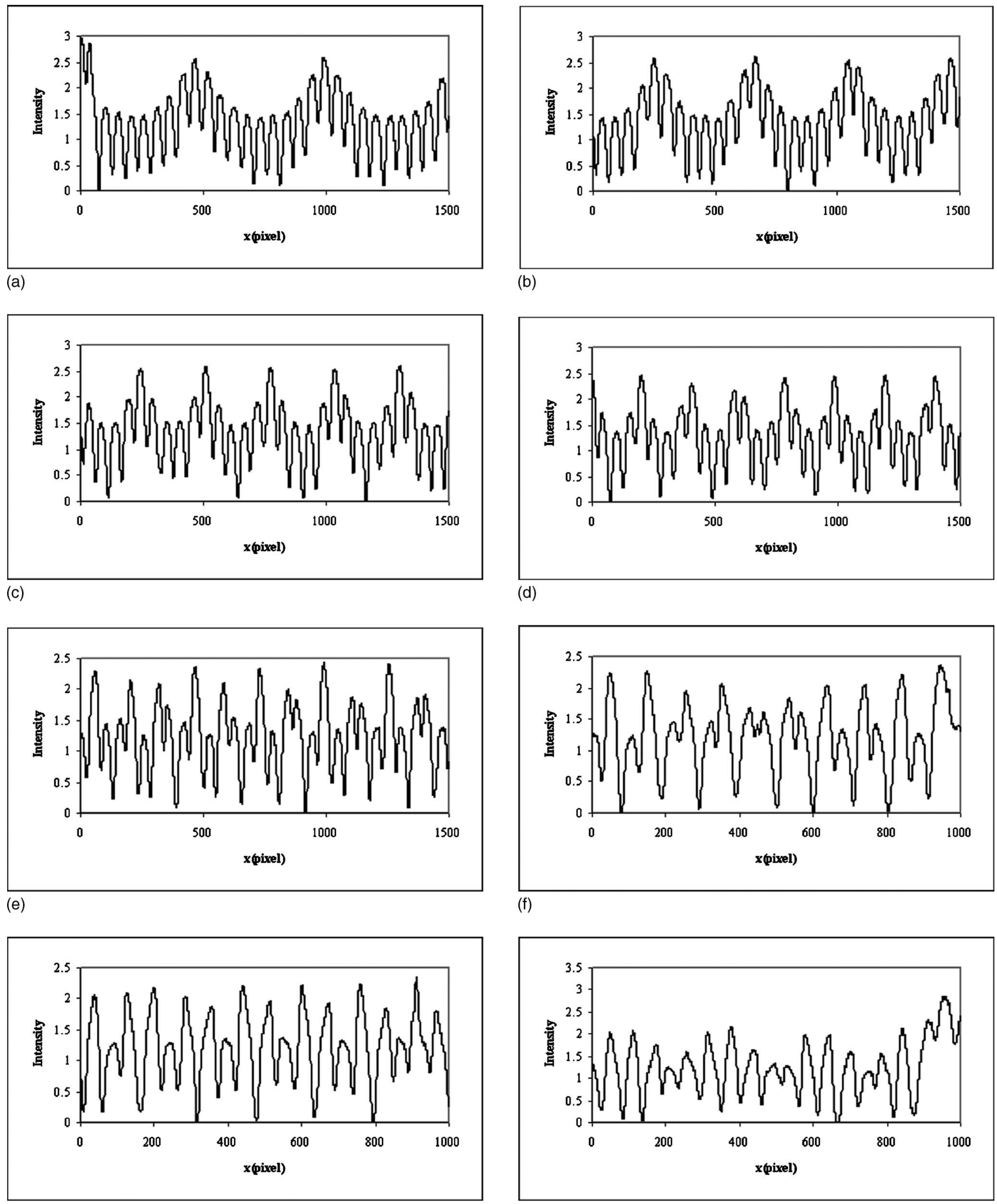


Figure 7. Microdensitometer traces for the sinusoidal test pattern contacted with silk fabric D at different applied spatial frequencies: (a) 0.375, (b) 0.5, (c) 0.75, (d) 1.0, (e) 1.5, (f) 2.0, (g) 2.5, and (h) 3.0 cycles/mm.

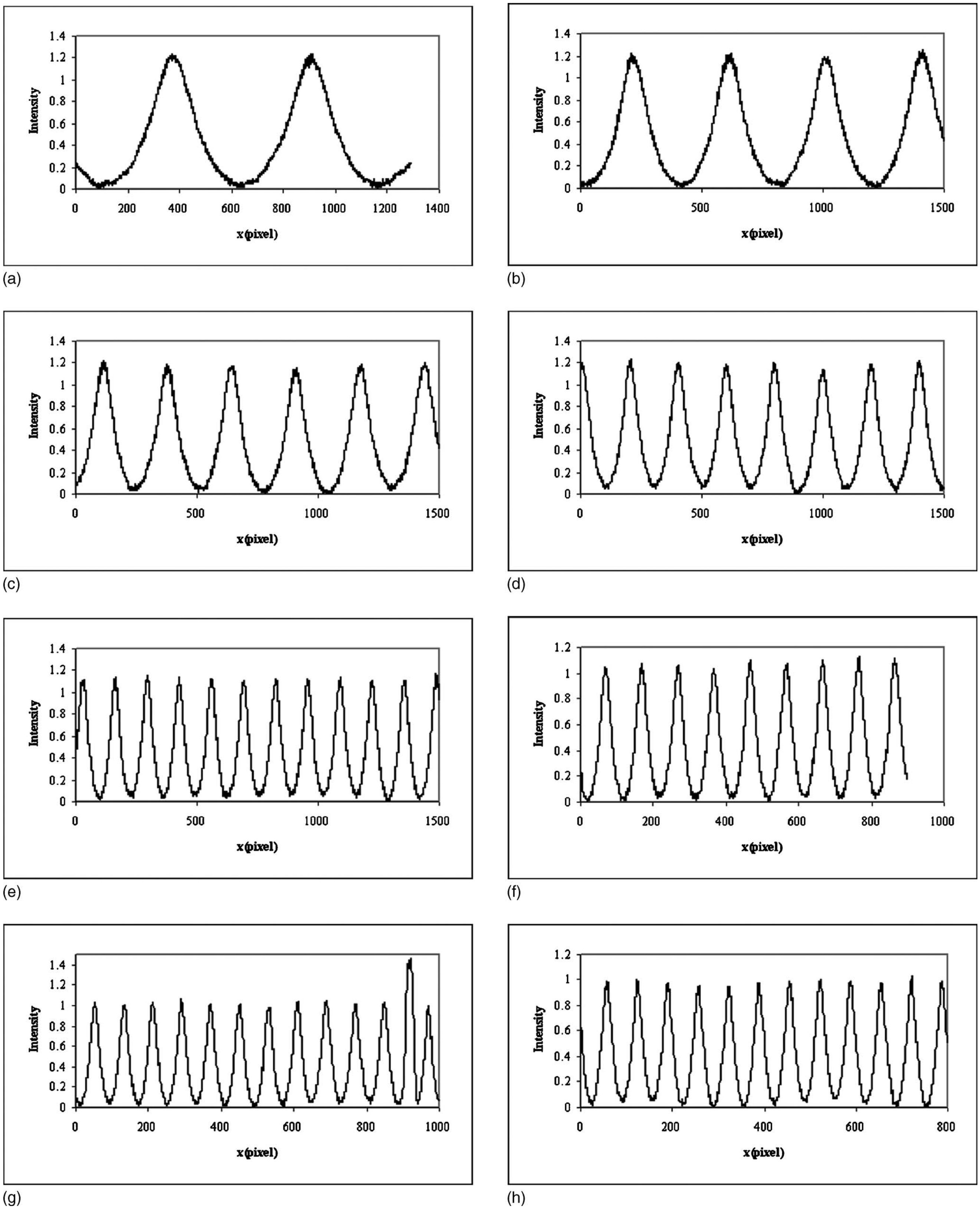


Figure 8. Microdensitometer traces for the sinusoidal test pattern contacted with paper at different applied spatial frequencies: (a) 0.375, (b) 0.5, (c) 0.75, (d) 1.0, (e) 1.5, (f) 2.0, (g) 2.5, and (h) 3.0 cycles/mm.

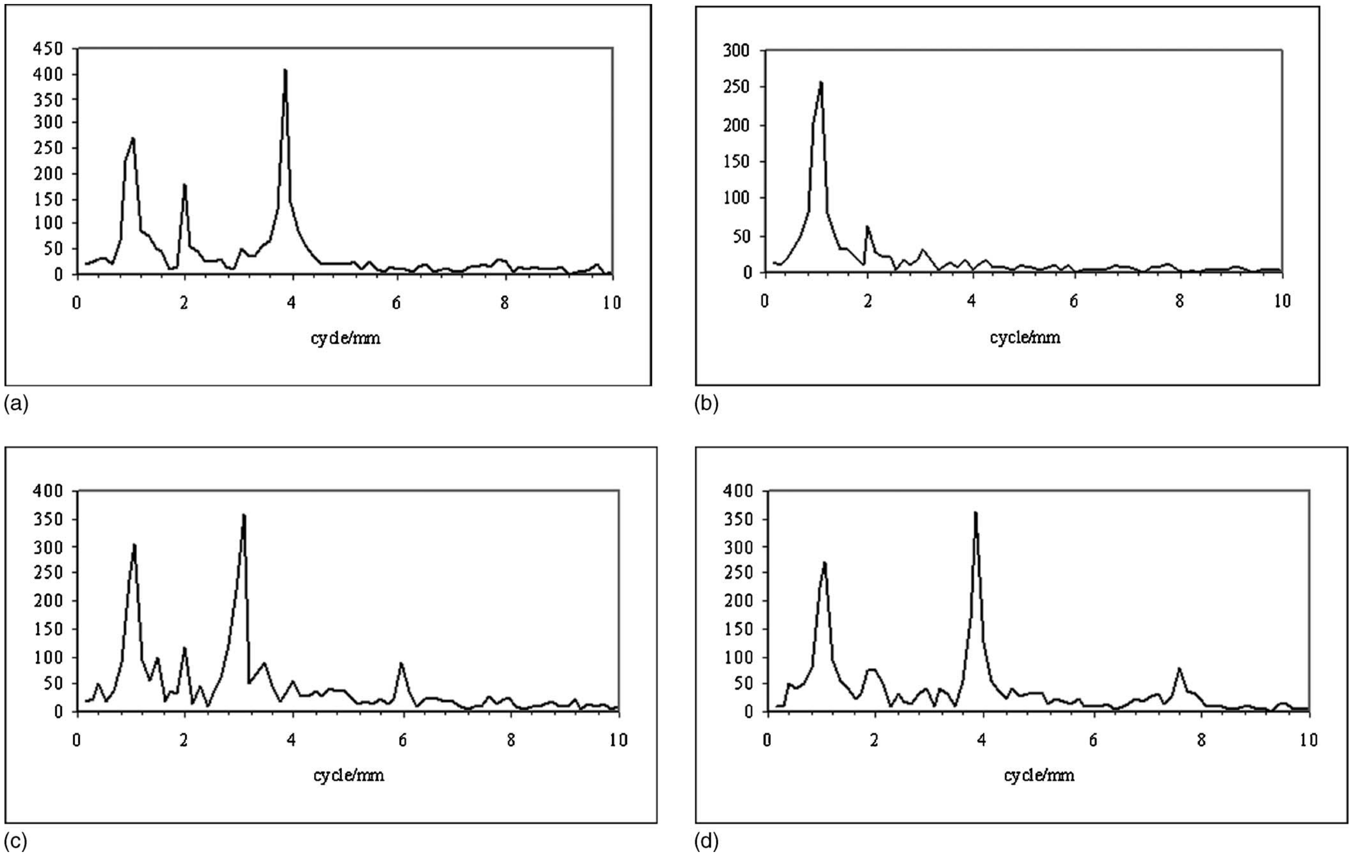


Figure 9. Fourier spectra of the reflectance of the sinusoidal test pattern with spatial frequency of 1.0 cycles/mm on (a) silk A, (b) silk B, (c) silk C, and (d) silk D.

A, B, C, and D, respectively. Figure 8 shows the densities of the sinusoidal test pattern in contact with an ink jet paper.

Each frequency was normalized to zero density. Because the silk fabric has a rough surface, an ink jet paper was selected as a reference for comparison with the silk fabric. Each data set contains two interference frequencies. The high frequency is the characteristic of weave and the low frequency is the reflection density of the sinusoidal test pattern in contact with the silk. Silks A, C, and D have a similar pattern because they are the same plain weave, while silk B is the twill style and has an intensity similar to that of the ink jet paper.

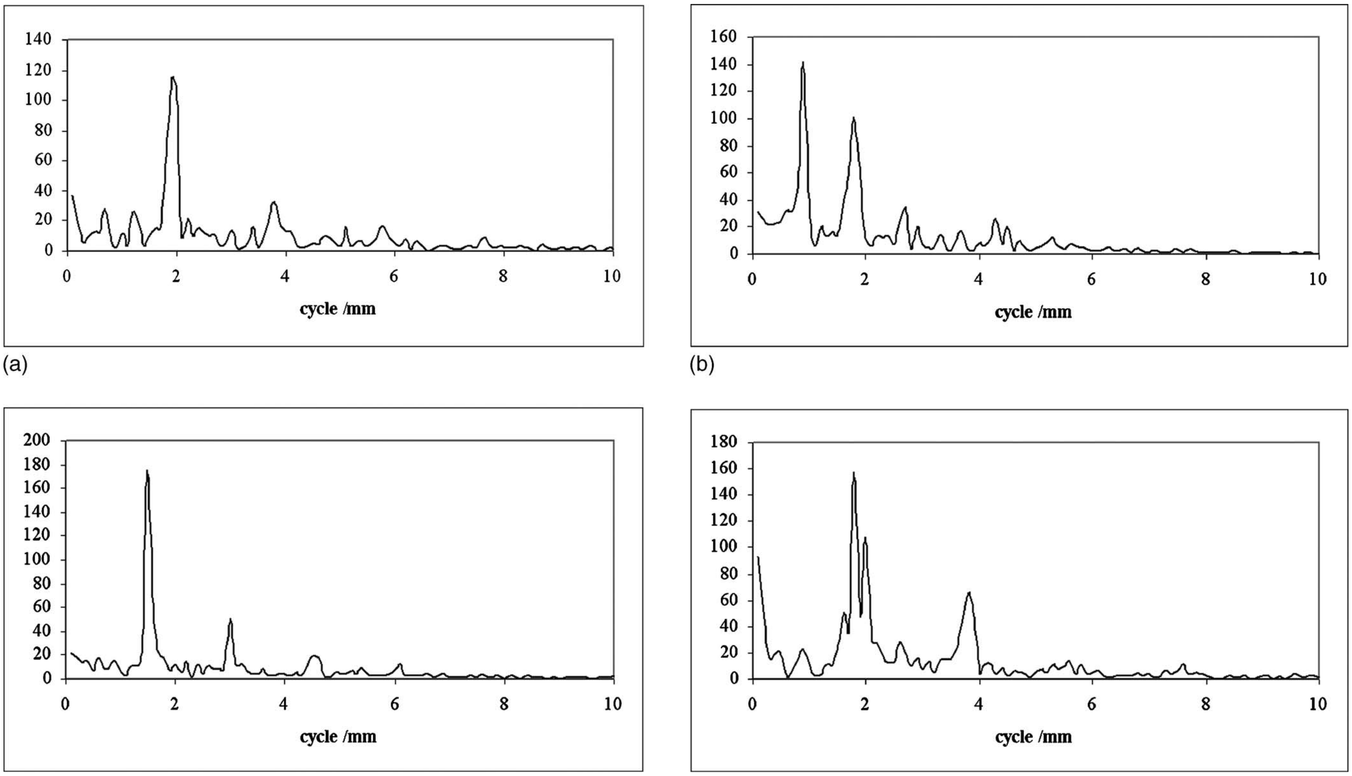
When considering the plain weave, the output spectrum increases in complexity when the spatial frequency of the sinusoidal test pattern increases because of the interference of the frequency of the weave with the sine wave. For silk B, the higher spatial frequencies of the twill weave exhibit only a small effect, similar to the result for the paper. The results of these experiments can be explained by the fact that each weft direction of the yarn typically passes over two and under two warp yarns. The frequencies of twill weave were less than the plain weave. The interference of the amplitude had little effect on the Fourier spectrum of silk B.

The FFT can analyze and separate the signals of the filtered data. Figure 9 illustrates the filtered reflectance of sinusoidal test pattern at 1.0 cycles/mm. All figures had asimilar spectrum at the spatial frequency of the signal of the sinusoidal test pattern. Other signals, for example, 4 cycles/mm of silk A or 3 cycles/mm of silk C were caused by the silk fabric itself.

Figure 10 shows the Fourier spectrum of the reflectance of the sinusoidal test pattern at 4 cycles/mm on the four types of silk. As expected, the frequency of the sinusoidal test pattern was not observed in all types of silk because its information was interfered with by the pattern of the silk fabric. Figure 10(b) does not have the peak at 4 cycles/mm but it shifted to 5.7 cycles/mm. This case may be caused by the direction of the silk fabric relative to trace.

Wicking Behavior of Silk Fabrics

The results for fabric wicking behavior are shown in Table II. These data indicated that a wicking anisotropy could exist relative to the warp and weft directions. As the ratios of warp/weft were smaller than unity, the weft direction of all silk fabrics could absorb more fluid than that of the warp direction. Wicking action describes the movement of fluid through an absorbing material. The water/2-octanol ratio describes the relative ability of the fabric to wick a hydrophilic liquid versus a hydrophobic liquid. From Table II, the silk fabrics B and C had a higher water/2-octanol ratio than the silk fabrics A and D. The rate of wicking of liquid in capillaries can be stated by the Lucas–Washburn equation,[17] Eq. (8), as shown below



(a) (b) (c) (d)

Figure 10. Fourier spectra of the reflectance of the sinusoidal test pattern with spatial frequency of 4 cycles/mm on (a) silk A, (b) silk B, (c) silk C, and (d) silk D.

Table II. Water (*W*) and 2-octanol (*O*) wicking rate of the four silk fabrics.

Fabric	Fluid	Warp (*P*) (cm)	Weft (*F*) (cm)	Warp/ weft (*P*/*F*)	Water/ 2-octanol (*W*/*O*)
A	Water	1.7	4.1	0.415	0.578
	2-octanol	2.8	3.9	0.718	
B	Water	1.85	4.0	0.463	0.728
	2-octanol	3.3	5.2	0.635	
C	Water	1.75	3.95	0.443	0.776
	2-octanol	2.0	3.5	0.571	
D	Water	1.15	3.0	0.383	0.567
	2-octanol	2.3	3.4	0.676	

$$l=(r\gamma\cos\theta/2\eta)^{1/2}t^{1/2}, \quad (8)$$

where l is the height of absorption at time t, r is the pore radius of the fiber, γ is the liquid surface tension, θ is the contact angle, and η is the liquid viscosity. Therefore, to provide capillary pressure to wick and retain the liquid, the size of the voids or pores has to be small. Since fabrics A and D have almost similar pore size and are larger than C and while fabric B has a smaller pore size, the wicking (water/2-octanol) of fabrics A and D is small and nearly equal due to the large pore size while those of fabrics B and C have a fast wicking rate because of the smaller pore size and large capillary force. Table II also indicates from the P/F values that all silk fabrics have a faster wicking rate in the weft direction than the warp direction. The water/2-octanol (W/O) ratio (the average value of water and 2-octanol from

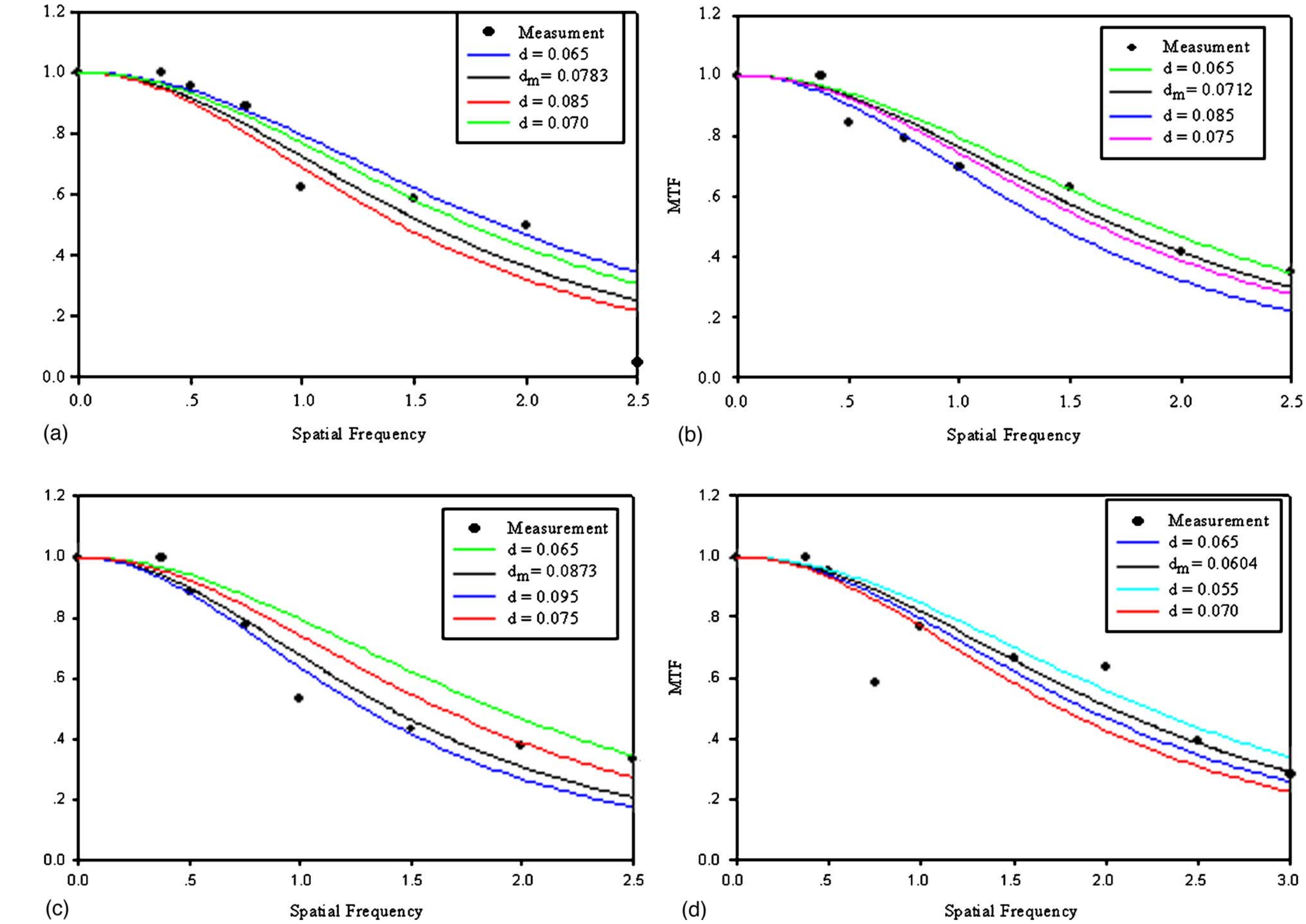


Figure 11. MTF of (a) silk A, (b) silk B, (c) silk C, and (d) silk D.

the warp and weft wicking rate) is an index of the relative ability of the silk fabric to wick hydrophilic versus hydrophobic fluids.[18] The silk fabrics A and D have a relatively hydrophobic surface while the silk fabrics B and C have a relatively hydrophilic character. It is suspected that scouring, mercerizing and bleaching treatments may contain some lubricating finish on the yarns as a processing aid, which gives rise to the hydrophobic behavior of the silk fabrics A and D.

MTF of Silk Fabrics

Figures 11(a)–11(d) show the measured MTF (dots) and its fitting curve from the empirical MTF equation, Eq. (5). The value of coefficient *d* corresponding to minimum rms error is 0.0783, 0.0712, 0.0873, and 0.0604 for the silks A, B, C, and D, respectively. The standard error has been included in the rms calculation.

From the MTF result, silk D had the smallest *d* value, i.e., it had the lowest scattering among these silks. However, the differences among these silk fabrics were not so large. The result indicated that the measurement of MTF of silk fabric using the contact sinusoidal method could be appropriate for finding the PSF of silk fabrics; however, only 45/0 geometry was measured. The 45° beam of the microdensitometer was made annularly to minimize the effects of any texture pattern that might be embossed on the sample surface.[19] The 45° beam unfortunately affected the shadow areas because of the rough surface of silk fabrics which was treated as noise. By use of Eq. (6), the *d* values obtained from MTF allow PSF to be calculated as shown in Fig. 12. One can see that the PSF of ink jet paper was the sharpest because of the smooth surface. Silk D produced the sharpest PSF among the four silk surfaces followed by silk B, silk A, and silk C. The reason for this result is explained and shown in Fig. 13.

As shown in Fig. 13, the light projected to the transparent image layer was absorbed and transmitted to the lower layer. The light was then scattered in the diffuse reflection layer, which was the silk in the present case. This phenomenon is represented as the MTF of the diffuse reflection layer. Finally, the scattered and reflected light in the diffuse reflection layer was absorbed in the transparent image layer again. The light scatting of silk D was the least and it had better sharpness than the others.

The n-Value from the Yule–Nielsen Effect

The *n*-values of silk A, B, C, and D were 1.645, 1.644, 1.688, and 1.636, respectively. Silk C gave the highest *n* value, which indicated that light scattering was slightly higher than

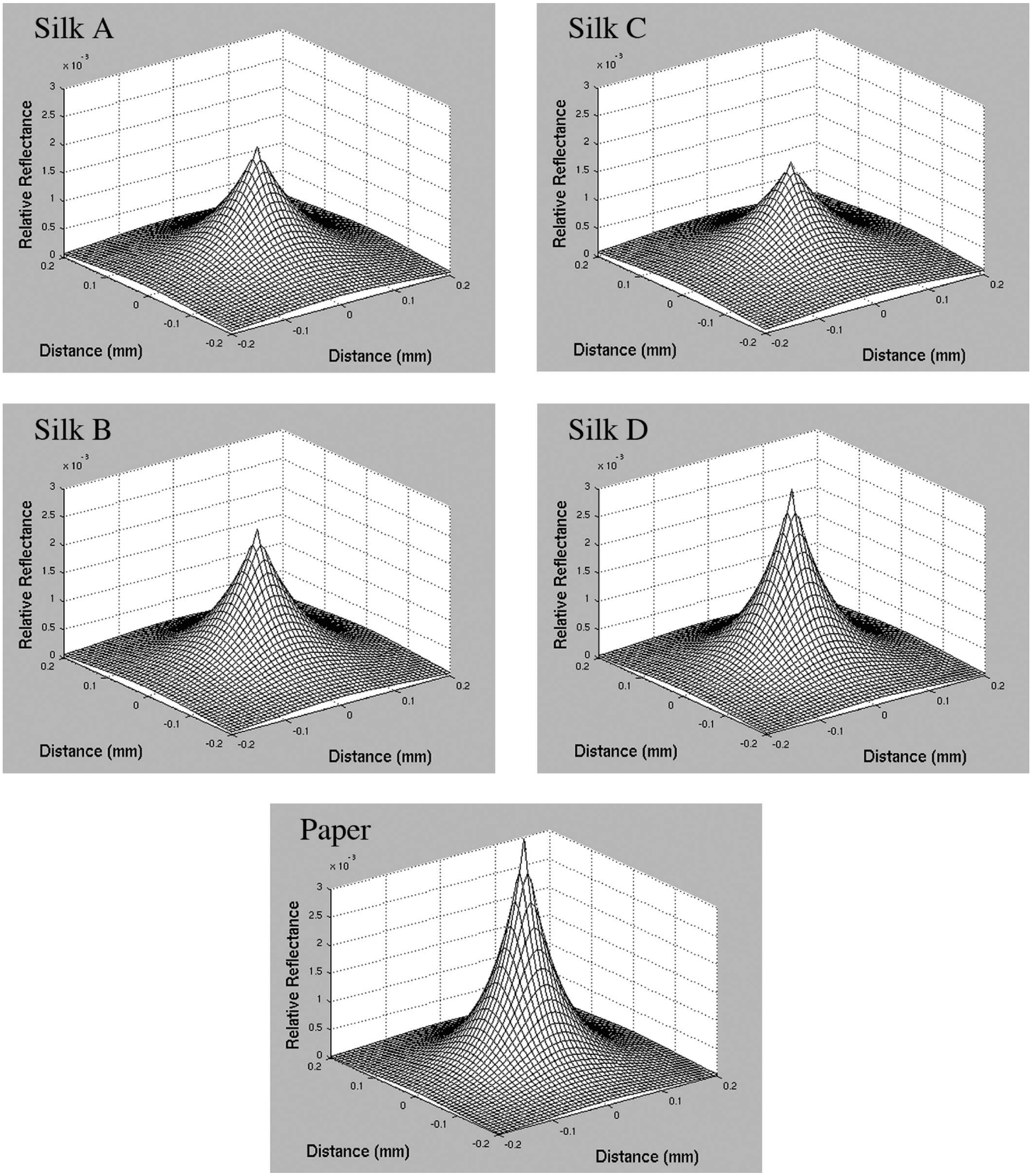


Figure 12. Point spread function of silk fabrics: silk A, silk B, silk C, silk D, and ink jet paper.

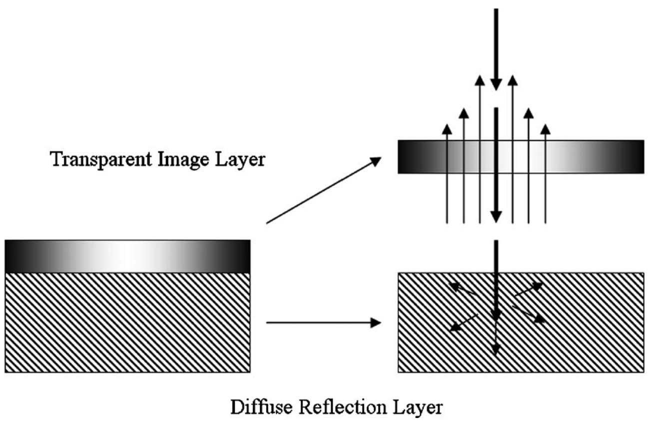
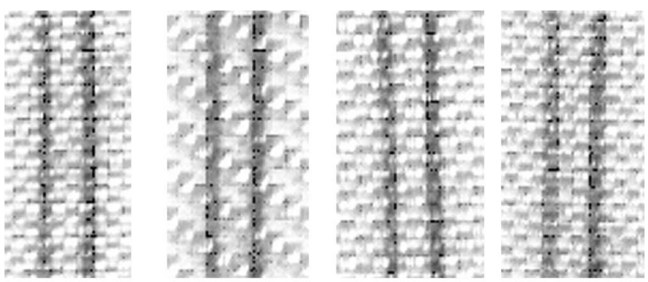
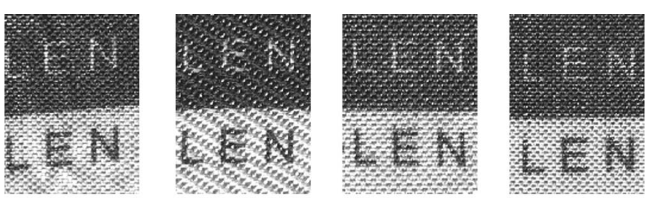


Figure 13. Diagram of light transmission through image and diffuse reflection layers.



(a) (b) (c) (d)

Figure 14. Images of a 1 mm vertical line printed on (a) silk A, (b) silk B, (c) silk C, and (d) silk D.



(a) (b) (c) (d)

Figure 15. Images of the text quality of 10 pt characters printed on (a) silk A, (b) silk B, (c) silk C, and (d) silk D.

other silks. In other words, the lowest *n* value meant less optical dot gain; so silk D had less optical dot gain effect than silks B, A, and C, respectively. However, this did not affect the total sharpness greatly.

Visual Quality of the Prints

Our measurements showed that these silks had similar light scattering properties. It was quite interesting to observe further the impact of ink spread on the silk fabrics. Therefore, the visual quality of the textile printing, the fineness and sharpness of detail was observed for each of the silks printed. This is shown in Figs. 14 and 15. It is probable that a better quality printed fabric could be produced on fabric D with better edge image and more uniform ink density then is shown in Figs. 14(d) and 15(d).

CONCLUSION

The ink jet inks were prepared and characterized for printability on four silk fabrics. Investigations of the fabrics interaction among the yarn, weave style and texture, and wicking behavior were carried out. The viscosities of the inks prepared were between 2.14 and 2.34 mPa s, which gave continuous and smooth printed images for all types of fabric. Silk fabrics A, C, and D were the plain weave while silk fabric B was twill weave. The hydrophilic/hydrophobic properties of the fabrics affected the print qualities. Silk fabric D was more hydrophobic than silk fabrics A, B, and C, respectively. The twill weave silk (silk B) did not give better sharpness than the plain weave even though it had a wider weaving area and the higher wicking value for 2-octanol.

The MTFs of silk fabrics were measured by the sinusoidal test pattern contact method at 45° beam geometry. Low-pass filtering was used to remove noise and frequency of the weave pattern. The peak of the FFT spectrum followed the sinusoidal test pattern. The FFT peak contained the light scattering of the silk fabric. The low frequency peak was selected for the calculation of the fabrics' MTF. The *d* values were 0.0604, 0.0712, 0.0738, and 0.0873 for silks D, B, A, and C, respectively. The Yule–Nielsen model was studied for comparison with the MTF technique. The *n* values from the Yule–Nielsen model were 1.636, 1.644, 1.645, and 1.688 for silks D, B, A, and C, respectively. The *n* values of this model were related to the *d* values of the MTF. Silk D had the smallest *d* and *n* values, i.e., it had relatively good quality in sharpness because the light scattering in this silk fabric was lowest while silk B had relatively small *d* and *n* values, next to those of silk D. This indicated that the mechanical dot gain played a vital role in image sharpness despite the optical dot gain. After having considered all relevant parameters of weaving technique and wicking behavior, it might be possible to recommend silks B and D as suitable for printing with the current ink jet ink. The MTF can be used for evaluating textile fabric quality in terms of the light reflection, but the fabric print quality still greatly depends on the physical property of the fabrics.

To conclude, to apply the MTF measurement method for evaluating (1) regularity, (2) light scattering, and (3) surface roughness of fabric, more research is needed especially on the anisotropic behavior and the three-dimensional structures of fabrics. Furthermore, ink distribution on fabric and ink-fabric interaction should be analyzed in order to know the reflected light from colorants dyed on fibers at various depths of the fabric. The measurement of reflected light from a fabric, as a three-dimensional object, must be taken into consideration.

ACKNOWLEDGMENTS

This project is partially supported by Thailand-Japan Technical Transfer Project under the Research Profile 21 Imaging Technology. The full financial support from the Thailand Research Fund under the TRF Senior Research Scholar Grant No. RTA4780004 (for Suda Kiatkamjornwong, the project head) is gratefully acknowledged. Research facility provided by the Imaging Laboratory of the Department of

Imaging and Printing Technology of Chulalongkorn University's Faculty of Science is highly acknowledged.

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