CHAPTER II

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Theoretical Background

2.1.1 Inkjet Printing System

Inkjet printing can be defined as a fluid control device with specific fluid control parameters. Microscopic ink drops are emitted under pressure from an orifice onto a substrate. The size of an orifice can vary from 10 to about 100 µm depending on the technology used. The color of the output also varies according to the type of printer used. Some printer outputs are in monochrome; some have a three-color output, using the primary subtractive colors magenta, yellow, and cyan; and some printers use the four-color technology, which includes inks in the primary subtractive colors plus the black ink. [2]

Two basic forms of inkjet printers comprise the majority of inkjet. The first is the continuous flow inkjet technology, and the second is the drop-on-demand or impulse inkjet technology. Both of these forms can be further divided into other categories according to the mechanism by which the drops are projected from the orifice onto the printing medium or to the novelty of the ink in its application to the inkjet technology.

2.1.1.1 Continuous flow inkjet

The continuous flow technology is based on the principle of continuous emission of ink from a high-pressure source (~550 psi) through a capillary of between 10 and 15 µm. Drops are generated at a frequency of 40-45 kHz.

A binary-deflection system, the ink stream undergoes a charge/no charge condition by a binary switching. In certain Hertz technology inkjet printers, individual drops, which are formed when the main stream of ink separates, pass through a high voltage field. Uncharged drops pass through the high voltage field and are deposited onto the substrate to form part of an image. Unwanted drops have a charge applied to them. When these charged drops pass through the high voltage, they are repelled by the electrode and are deflected into a gutter. This system is shown in Figure 2.1
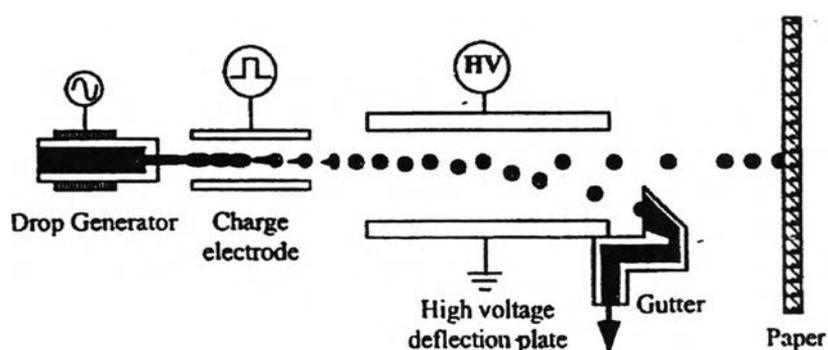
Figure 2.1 Continuous inkjet: A binary-deflection system

Figure 2.2 shows a multiple deflection system, drops are charged and deflected to the media at different levels.
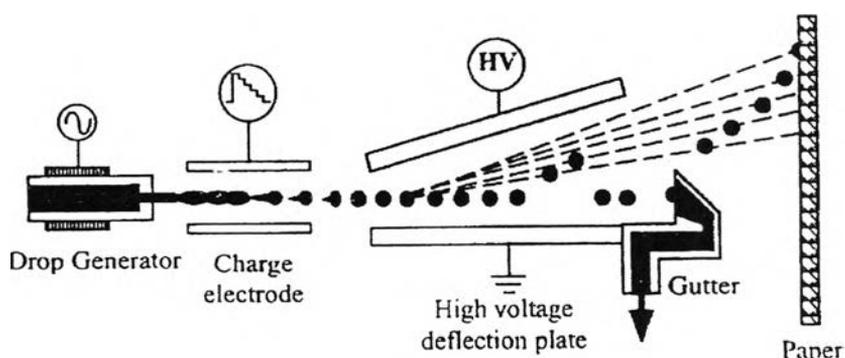
Figure 2.2 Continuous inkjet: A multiple-deflection system

2.1.1.2 Drop-on-demand inkjet [3]

The basic concept of drop-on-demand or impulse inkjet printing is to eject a drop of ink from a nozzle onto a substrate. The drop is emitted by means of binary pulse acting on a mechanism, which delivers the energy to produce such a drop. The ink is contained in a chamber. The forces of hydrostatic pressure cause the ink to form concave meniscus. The nozzle may vary from about 40 micrometer to about 100 micrometer. An electrical driving pulse acts on the chamber, causing the volume of ink to decrease, thus emitting a drop of ink from the orifice at a relatively high velocity. The frequency at which the drops are ejected varies greatly depending on the manufacturer of the system. The operating frequencies in general vary in the range of 2-8 kHz. The velocity of the drops usually ranges between 1 and 3 m/s. Depending on the mechanism used in the drop formation process, the technology can be categorized into four major methods: thermal, piezoelectric, electrostatic, and acoustic inkjet. On the market today are using either the thermal or piezoelectric principle. Both the electrostatic inkjet and acoustic inkjet methods are still in the development stage with many patents pending and few commercial products available.

A thermal inkjet consists of an ink chamber having a heater with a nozzle nearby. With a current pulse of less than a few microseconds through the heater, heat is transferred from the surface of the heater to the ink. The ink becomes superheated to the critical temperature for bubble nucleation, for water based ink, this temperature is around 300 °C. When the nucleation occurs, a water vapor bubble instantaneously expands to force the ink out of the nozzle. Once all the heat stored in the ink is used, the bubble begins to collapse on the surface of the heater. Concurrently with the bubble collapse, the ink droplet breaks off and excels toward the paper. The whole process of bubble formation and collapse takes place in less than 10 micrometer. The

ink then refills back into the chamber and the process is ready to begin again. Depending on the channel geometry and ink's physical properties, the ink refill time can be from 80 to 200 microseconds. This process illustrated in Figure 2.3 shows the drop formation of thermal inkjet process.

The piezoelectric inkjet depends on the piezo-ceramic deformation mode. The technology can be classified into four main types: squeeze, bend, push, and shear. A squeeze-mode inkjet can be designed with a thin tube of piezo-ceramic surrounding a glass nozzle or with a piezo-ceramic tube cast in plastic that encloses the ink channel. In a typical bend-mode design, the piezo-ceramic plates are bonded to the diaphragm forming an array of bi-laminar electromechanical transducers used to eject the ink droplets. A bend-mode piezoelectric inkjet which be showed as Figure 2.4.
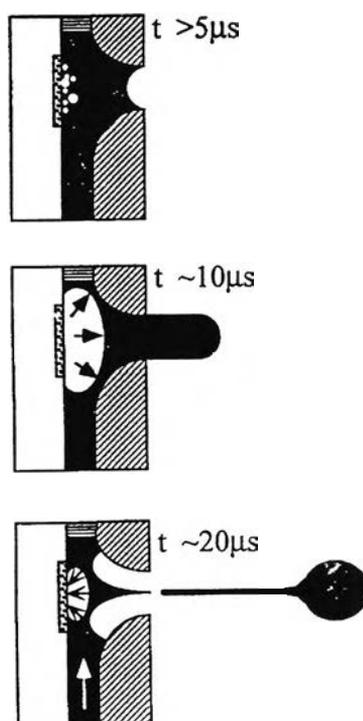
Figure 2.3 Drop formation process of a thermal inkjet.

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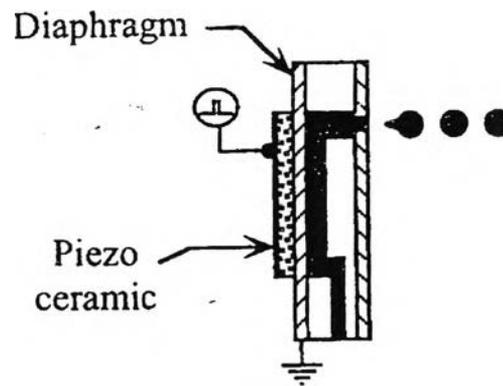
Figure 2.4 A bend-mode piezoelectric inkjet design.

In a push-mode design as the piezo-ceramic rods expand, they push against ink to eject the droplets. In theory, piezo-drivers can directly contact and push against the ink. However, in practical implementation, a thin diaphragm between piezo-drivers and ink is incorporated to prevent the undesirable interactions between ink and piezo-driver materials. Figure 2.5 shows a push-mode piezoelectric inkjet.
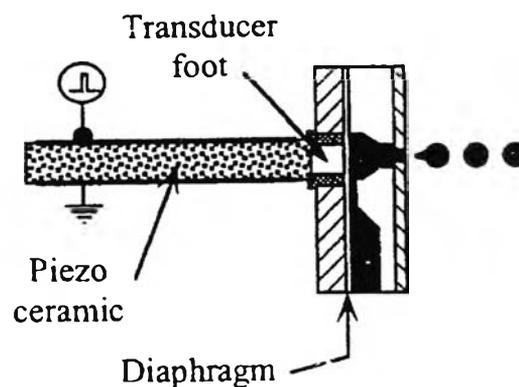
Figure 2.5 A push-mode piezoelectric inkjet design.

In both the bend- and push-mode designs, the electric field generated between the electrodes is in parallel with the polarization of the piezo-material. In a

shear-mode printhead, the electric field is designed to be perpendicular to the polarization of the piezo-driver. The shear action deforms the piezo-plates against ink to eject the droplets. In this case, the piezo-driver becomes an active wall in ink chamber. Interaction between ink and piezo-material is one of the key parameters of a shear-mode printhead design. Figure 2.6 shows a shear-mode piezoelectric inkjet.
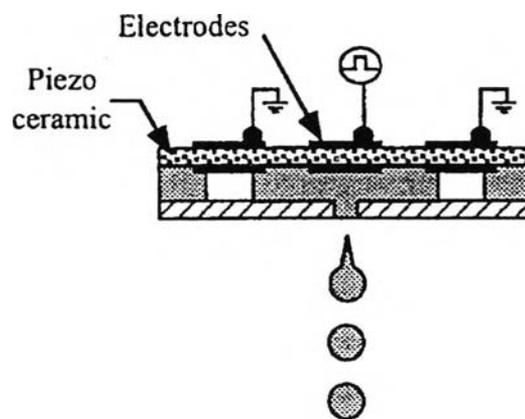
Figure 2.6 A shear-mode piezoelectric inkjet design

The deformation of the piezo-ceramic material causes the ink volume change in the pressure chamber to generate a pressure wave that propagates toward the nozzle. This acoustic pressure wave overcomes the viscous pressure loss in a small nozzle and the surface tension force from ink meniscus so that an ink drop can begin to form at the nozzle. When the drop is formed, the pressure must be sufficient to expel the droplet toward a recording media. The basic pressure requirement is showed in Figure 2.7.

Viscous
pressure loss
(0.5-1.0 atm)

Acoustic
Pressure

Surface tension
pressure rise
(<0.1 atm)

Dynamic pressure
of liquid
(~0.5 atm)
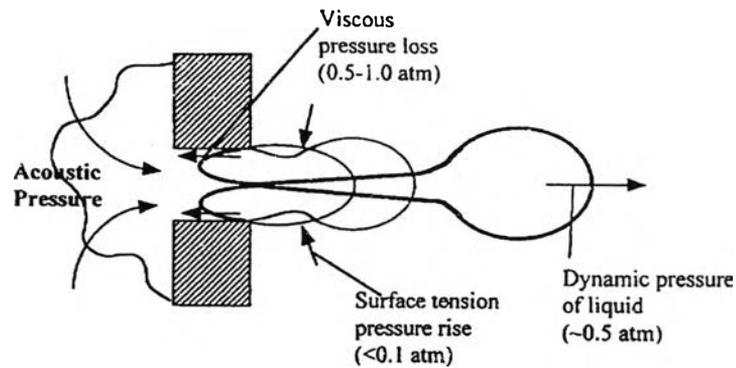
Figure 2.7 The basic pressure requirement for ejecting an ink droplet

2.1.2 Ink Formulation

2.1.2.1 Colorant [2]

The colorant first used for ink jet printing of documents was water-soluble dyes as opposed to pigment because a soluble bester satisfied the runability requirements than dispersion. However, this is no longer the case, and pigment inks are now available that do not clog up orifices and have a color gamut approaching that of dyes. Further, with today's emphasis on light fastness and water fastness, pigments are a natural choice.

2.1.2.2 Solubilizing Agent/Dispersant

Since light fastness and water fastness are favored by dyes of limited solubility, a solubilizing agent is usually the next component to be selected for dye-based inks. In the simplest case, it may be just a co-solvent such as an alcohol which compensates for the hydrophobic nature of the dye and allows the resulting mixture to match its solubility parameter. It should be noted that it is not sufficient just to match the overall value but also the individual components characterizing the hydrogen bonding, polar and van der Waals interactions. Another simple approach is to control the acidity of the vehicle so as to have the dye in an ionized state by inducing an

acid/base reaction. For example, anionic dyes would require a high pH, but not so high that the increased ionic strength collapses the electric double layer and thus shields the electrostatic repulsive force.

2.1.2.3 Defoamer

Foam is produced when air is entrained in the ink as a result of agitation. This can occur in manufacturing during mixing and filling operations, as well as in the ink jet printing process. It is particularly a problem with continuous ink jet systems that recycle the un-printed drops. Aside from run-ability problems, print quality can be compromised if there are air bubbles in the deposited ink film giving rise to pin holes and craters.

Figure 2.8 illustrates the structure of foam as a honeycomb network of bubbles separated by thin liquid films that form three-way junctions. The capillary pressure at these junctions, which is less than atmospheric, drives their drainage and surface viscosity provides the resistance to flow.
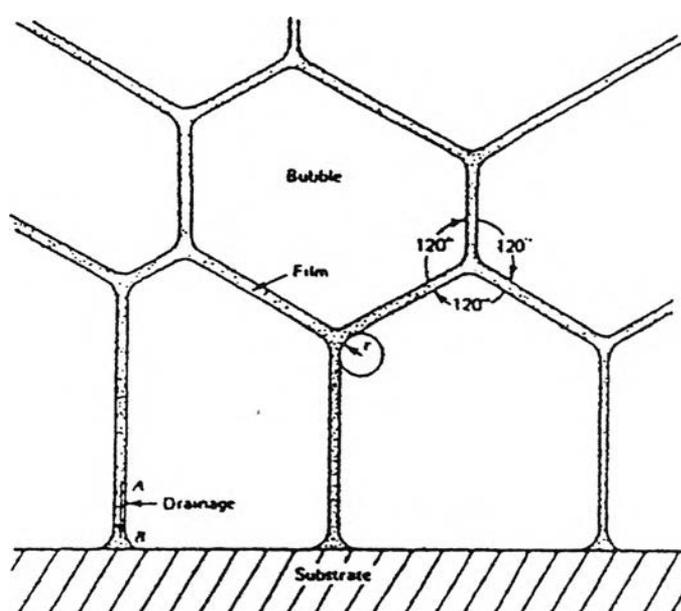
Figure 2.8 Structure of foam

The first approach in solving a foaming problem is to attack it at the source and minimize the introduction of organic impurities during the dye synthesis or remove them as a post operation such as dialysis or ultrafiltration. If this fails, one should select some defoamers using the above guidelines with the additional requirement that they be absorbed strongly enough at the air/water interface so that they can displace the foaming agents. Another criterion, especially for continuous ink jet systems, is that the defoamer not be absorbed by any components of the fluid handling system, such as filters, and lose their effectiveness. This behavior is observed because hydrophobicity is driving the defoamer out of the water phase to whatever interface is available. One way to try to compensate for this phenomenon is to use excess defoamer, especially above its critical micelle concentration, so that the micelles continue to replenish the defoamer as it is removed. Finally, defoamers may be classified into the following chemical types: (1) alcohols, (2) fatty acids and derived esters, (3) amides, (4) phosphate esters, (5) metallic soaps, (6) silicone oils, and (7) chemicals with multiple polar groups

2.1.2.4   Humectant

After a shutdown, the ink can dry to a hard, crystalline crust, and this can cause crooked jets or even block an orifice. Further, deposits can form on the charge plate and catcher of continuous printers, and they then interfere with their proper functioning. Thus the ink must exhibit sufficient humectancy that redissolution or redispersion can readily occur. Another desirable property would be a low evaporation rate, which also extends life by reducing the increase in colorant concentration for recycling systems. A co-solvent included which is nonvolatile and not very viscous, such as a glycol, can control this problem. However, it should be

kept in mind that the dry time of the image may be extended excessively, if too much is added.

2.1.2.5 Binder

The binder is a polymer capable of film formation such as an acrylic resin, and it may be added to the formulation as a water soluble type or in an emulsion/dispersion form. In fact, if the polymer contains acidic/basic groups, varying the pH can transform it from one state to the other. For example, in the case of carboxyl groups low pH suppresses their ionization and the polymer is in the emulsion form because there is no electrostatic repulsion between the chains. As the pH increases, the acidic groups ionize, and the resulting repulsion forces the chains to separate and go into solution. Further increases in pH will eventually raise the ionic strength to the point that the electric double layer will start to collapse. This results in the chain curling and ultimately precipitation of the polymer. Another consequence of these configuration changes is that the viscosity rises up to a maximum, at which point the chains are fully extended and somewhat inflexible due to the electrostatic repulsion; and beyond this it will decline. Thus ionic polymers can also be used as viscosity modifiers.

The binder provides adhesion of the dye to the substrate by forming a film that encapsulates it upon drying. In the case of a solution polymer, this occurs by the polymer precipitating out to surround and immobilize the dye. On the other hand, an emulsion polymer accomplishes this by coalescence.

2.1.3 Properties of Inkjet Inks

2.1.3.1 Viscosity [4, 5]

The viscosity of the ink is of primary importance. A humectant such as glycol is the primary constituent that affects this parameter. In inkjet systems, the amount of

humectant will affect the degree of crusting caused by dye precipitation. Too much humectant would greatly hinder the flow of ink through a 10 μm nozzle. The drop-on-demand printers require more viscous ink than the continuous inkjet printers. This is because, instead of high pressure, the drop-on-demand system uses an acoustic wave, usually produced by a piezoelectric transducer, to emit and propel an ink drop. Acceptable viscosities are no greater than 20 mPa s, and preferably in the range of about 1.0 to about 10.0, preferably 1.0 to 5.0 mPa s at room temperature.

Another aspect of viscosity is the need to have the ink behave as close to a Newtonian fluid as possible. The ideal system maintains a constant viscosity regardless of shear rate. In other words, the best system doesn't become more or less fluid as it is drawn from the reservoir, shot through the nozzle, or contacts the substrate.

2.1.3.2 Specific gravity

The specific gravity of the fluid is needed to determine the weight of the mass to be propelled for velocity studies, and to determine other physical properties.

2.1.3.3 Surface tension

Surface tension is one of the primary factors determining where the actual drop will form in continuous inkjet printers. In drop-on-demand printers, it helps to regulate control of the concave meniscus to hold ink in the system. Once the ink has been deposited onto the printing substrate, the interaction of the surface dynamics of both ink and paper play a major role in how the final form of the dot will appear.

Surface tension of the ink is a measure of the energy with which the liquid molecules cling to each other. To have an optimum drop formation, the high surface tension gives the spherical drop. Of the practical ink solvents, water provides the highest surface tension on the order of 72 mN m^{-1}. When used in an actual

formulation, this value is reduced to 40-60 mN m^{-1} by the other ink components, including colorants, polymers, and additives. Solvent-based inks have surface tensions closer to 20-30 mN m^{-1}. While high surface tension is helpful for drop formation, it is undesirable for wetting or non-porous surfaces such as plastic films, metal cans, and foils. These are low surface energy substrates, and high surface tension liquids tend to form beads, rather than wet them. It is not usual to corona treat plastic films to improve wetting, adhesion, and drying of water-based inks, including inkjet inks.

A surface tension in the range of about 20 mN m^{-1} to about 70 mN m^{-1} and, more preferably, in the range 30 mN m^{-1} to about 50 mN m^{-1}. Control of surface tensions in aqueous inks is accomplished by additions of small amounts of surfactants.

2.1.3.4 Conductivity

The continuous inkjet system imposes an electrical charge on the drops, ink conductivity is thus important for this process. Conductivity for drop-on-demand systems is not an issue. The units of conductivity are μS cm^{-1} (microsiemens per centimeter) and the range of conductivity operation is usually 1,000-10,000. This is controlled by incorporation of soluble salts in the ink, making certain that they are non-corrosive. In many instances, the dye, or salts brought into the formulation with the dye, will provide conductivity as well.

2.1.3.5 pH

The pH of the ink is critical for several reasons. First of all, the solubility of the dye is greatly affected by pH. The hue of some dyes will change if they go from a low to high pH value. There must be a correlation between the pH values of the ink and of the printing media; otherwise, the archival quality of the print may be deteriorated. Another reason for controlling pH of the ink is that the orifice of some

inkjet systems may be made of material that is affected by pH. If this is the case, the pH of the ink should be close to neutral to prevent any corrosion. Dye based inkjet inks suitable for use with inkjet printing systems should have a pH in the range of 4 to 6. [6]

2.1.4 Silk Fabric

Silk is the only commercially valuable fiber that in its natural state is a continuous filament. Several types of spider webs do not quite make the grade. The silkworm may spin as much as a mile of silk to make its cocoon. As spun, silk is two fibers of the protein fibroin literally stuck together in a matrix of a chemically similar protein gum called sericin. The gum is removed by soaping, leaving the degummed silk fibers behind. These fibers are so valuable that their weight is frequently increased by treating them in tin chloride solutions followed by sodium phosphate to precipitate insoluble salts, followed by sodium silicate. The resulting fibers may contain anywhere from 25-60 %wt of tin salts. A popular misconception is that the quality of silk is indicated by its hand or scoop the crunching noise made when the fabric is crushed.

The chemistry of silk in some response parallels that of wool. The protein (polyamide) fibroin has the same general formula, but now there are only four major amino acids on hydrolysis (there are more than seven other), and so there are essentially only four –R groups hanging from the polymer chain. Furthermore, unlike wool, there are no –R groups with constituent amino, carboxylic acid or disulfide groups, (-NH$_2$, -COOH, -S-S). Silk contains no sulfur, and the only amino and carboxylic acid groups come as end groups with the following general formula:
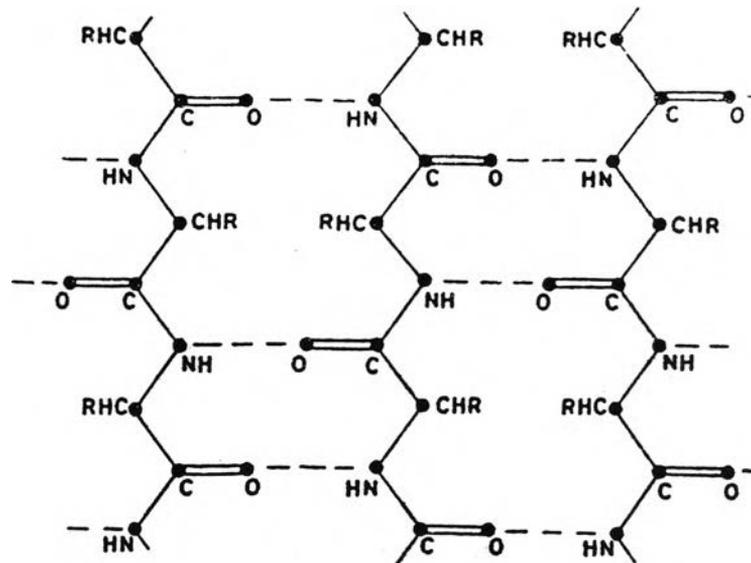
Figure 2.9 Extended-chain molecules of silk fibroin [7]

Morphologically also, silk is simple. Its molecules are not coiled into helixes and in fact the molecular structure of silk is more like that of fully extended wool. This is reflected in the lower elasticity of silk. However, the molecules are arranged into regions that are crystalline and amorphous, ordered and disordered, much like those of cellulose. Interestingly, silk dyes with direct dyes much more readily than does wool. [7]

Silk is essentially used in very expensive luxury goods. It has been able to withstand competition from synthetic fibers in many high-quality textile applications because of its excellent dyeing characteristics, high moisture and absorbency, and heat-preserving property. It has one major drawback that it does not blend easily with other fibers. [8]

Silk has a specific gravity of 1.25-1.30 and a moisture regain of 11% under standard conditions. Silk is soluble in hydrogen bond breaking solvents such as aqueous lithium bromide, phosphoric acid, and cuprammonium solutions. It exhibits

good heat insulating properties and is little affected by heat up to 150°C. Silk has

moderate electrical resistively and tends to build up static charges.

End-use Properties

2.1.4.1 Appearance

The smooth, translucent surface of silk gives it a high luster, while the

triangular shape of the fiber provides highlights that cause silk fabrics to sparkle.

2.1.4.2 Comfort

The hand of silk is usually considered to be the most pleasant of all

fibers. It is often described as smooth, crisp, soft, and dry. The pleasant hand comes

about through a combination of smooth surface, fineness of fiber, and ability to

absorb moisture. The smooth, fine yarns do not trap air well and the protein structure

of silk allows a high level of moisture absorption and good wicking. Thus, silk

garments are comfortable on all but the most hot and humid days.

2.1.4.3 Maintenance

The smooth surface of silk fibers prevents dirt from attaching itself

readily, so silk fabrics do not soil easily. Fibroin is destroyed by strong acid and alkali,

and even weak alkali in long contact with the fiber will cause some damage. Silk

fabrics have good dimensional stability and usually will not shrink or stretch. The

resiliency of the fiber assures that it will not wrinkle readily. Silk is damaged by high

temperatures and will yellowing.

2.1.4.4 Durability

Silk is a moderately strong fiber with good resistance to abrasion. It decomposes in strong sunlight and when exposed to atmospheric fumes. The sensitivity of silk to perspiration is of greater concern. Silk has a dry tenacity of 2.8-5.2 g d^{-1} and a wet tenacity of 2.5-4.5 g d^{-1}.

2.1.5 Fourier Transforms

In the analysis of spatial image detail that Fourier transform theory and the spatial frequency analysis of images can be greatly beneficial, for example, the modulation transfer function (MTF) which is the Fourier transform (FT) of the spread function may be a more useful quantity in practice. Spatial frequency sometimes proves a conceptual stumbling block, and the analogy with temporal frequency in the frequency analysis of electrical communication systems is helpful in this respect.

The MTF describes the extent to which spatially sinusoidal exposure inputs arc modulated in the image. From the viewpoint of desirable test objects for photographic image evaluation, pointed out the interesting result that the image of a sinusoidal object is also sinusoidal but with reduced modulation depending only on the spatial frequency. However the main stimuli for applying Fourier methods to optical imaging systems pointed out the full implications of replacing the convolution of spread functions by the product of their Fourier transforms.

Since the Fourier transform is an essential mathematical tool for understanding the MTF.

Definition of Fourier Transform

If $f(m,n)$ is a function of two discrete spatial variables m and n, then we define the two-dimensional Fourier transform of $f(m,n)$ by the relationship

$$F(\omega_1, \omega_2) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} f(m,n) e^{-j\omega_1 m} e^{-j\omega_2 n} \qquad (2.1)$$

The variables ω_1 and ω_2 are frequency variables; their units are radians per sample. $F(\omega_1, \omega_2)$ is often called the frequency-domain representation of $f(m,n)$. $F(\omega_1, \omega_2)$ is a complex-valued function that is periodic both in ω_1 and ω_2 , with a period of 2π. Because of the periodicity, usually only the range $-\pi \le \omega_1, \omega_2 \le \pi$ is displayed. Note that $F(0,0)$ is the sum of all the values of $f(m,n)$. For this reason, $F(0,0)$ is often called the constant component or DC component of the Fourier transform. (DC stands for direct current; it is an electrical engineering term that refers to a constant-voltage power source, as opposed to a power source whose voltage varies sinusoidal.)

The inverse two-dimensional Fourier transform is given by

$$f(m,n) = \frac{1}{4\pi^2} \int_{\omega_1 = -\pi}^{\pi} \int_{\omega_2 = -\pi}^{\pi} F(\omega_1, \omega_2) e^{j\omega_1 m} e^{j\omega_2 n} d\omega_1 d\omega_2 \qquad (2.2)$$

Roughly speaking, this equation means that $f(m,n)$ can be represented as a sum of an infinite number of complex exponentials (sinusoids) with different frequencies. The magnitude and phase of the contribution at the frequencies (ω_1, ω_2) are given by $|F(\omega_1, \omega_2)|$.

2.1.6 The Line Spread Function

The line spread function of an imaging system is defined as the response of the system to a line input. A line input may be represented by a single delta function, $\delta(x_1)$, which lies along the y_1 axis as shown in Figure 2.10. The line spread function depends only on the x-variable, and using the convolution relationship between input and output, will be defined as

$$l(x) = \int \int_{-\infty}^{+\infty} \delta(x - x_1) h(x_1, y_1) dx_1 dy_1 \qquad (2.5)$$

By the sifting property of the delta function;

$$l(x) = \int_{-\infty}^{\infty} h(x, y_1) dy_1 \qquad (2.6)$$

Thus the line spread function is obtained from the point spread function by integrating over one variable.

Point spread functions of photographic processes are usually rotationally symmetrical, i.e.

$$h(r) \equiv h(x, y), where \ r^2 = x^2 + y^2 \qquad (2.7)$$
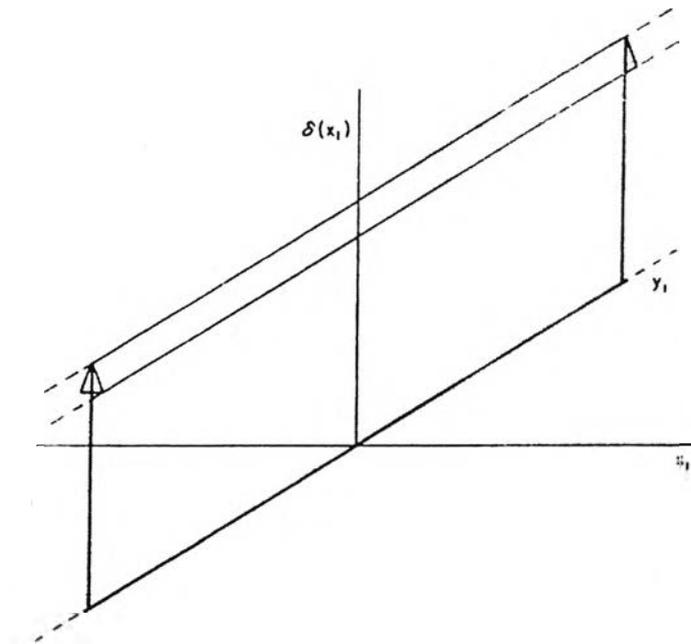
Figure 2.10 A line input $\delta(x_1)$.

In this case, the point spread and line spread functions are related as Abel transform pairs:

$$l(x) = 2\int_x^\infty h(r)\left(r^2 - x^2\right)^{-\frac{1}{2}} r\,dr$$

$$h(r) = -\frac{1}{\pi}\frac{d}{dr}\left(\int_r^\infty \frac{l(x)\,dx}{x\left(x^2 - r^2\right)^{\frac{1}{2}}}\right) \qquad\qquad (2.8)$$

Although calculation of the line spread function from the point spread function is quite straightforward, the reverse operation is seen to be rather complicated, both for rotationally symmetrical and non-symmetrical point spread functions.

If the photographic point spread function is rotationally symmetrical it will be completely specified by a section $h(r)$, or by the one-dimensional line spread function, $l(x)$. In practice the line spread function is often the more useful of the two functions, and it may also be easier to measure experimentally. Suppose the input is an opaque edge lying along the y-axis such that

$$f(x) = 0(x < 0); f(x) = 1(x \geq 0) \hspace{2cm} (2.9)$$

Applying the convolution relationship, the edge spread function, e(x), is given by

$$e(x) = \int \int_{-\infty}^{+\infty} f(x - x_1) h(x_1, y_1) dx_1 dy_1$$

$$= \int_{-\infty}^{x} l(x_1) dx_1 \hspace{2cm} (2.10)$$
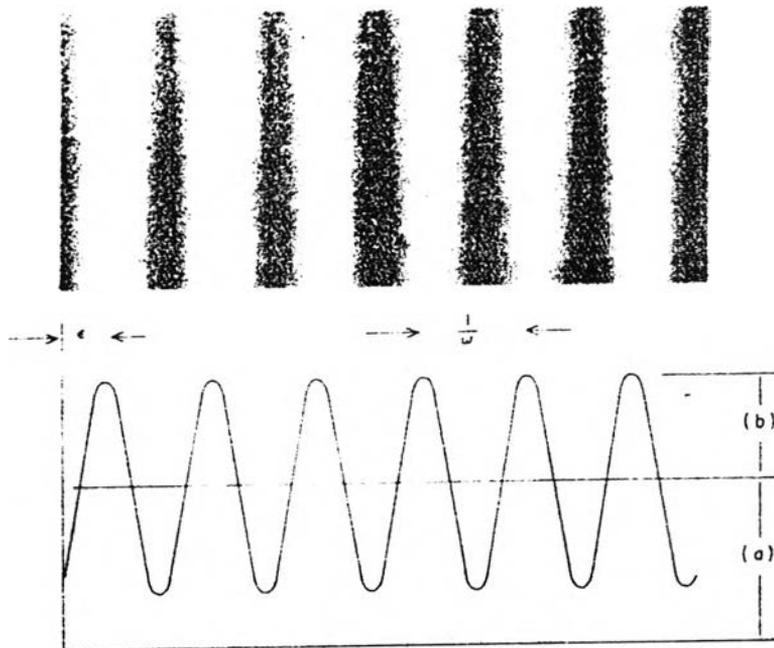
Figure 2.11. A one-dimensional sine wave input, with spatial frequency ω, modulation b/a, and phase ε.

The edge spread function is an integration of the line spread function. From equation (2.10) it follows that the line spread function is given by the differential of the edge spread function:

$$l(x) = \frac{d}{dx}(e(x))$$ (2.11)

2.1.7 The Modulation Transfer Function

Modulation Transfer Function (MTF) is the spatial frequency response of an imaging system or a component; it is the contrast at a given spatial frequency relative to low frequencies. It is a measurement used to describe the ability of lens, films, and other optical components to image or to reproduce the detail contained in an object.

Lens and film resolving power was measured in lines (or line pairs) per millimeter (lp/mm) easy to understand, but poorly standardized. It was obtained by photographing a chart and looking for the highest resolution pattern where detail was visible. Because perception and judgment were involved, different measurements of the same film or lens were highly inconsistent. Lines per mm would have been more useful if it were measured at a well-established contrast level, but that was not so easy; it would have required expensive instrumentation. The problem of specifying resolution and perceived sharpness was solved with the introduction of the Modulation transfer function (MTF), a precise measurement made in frequency domain. The MTF is the spatial frequency response of an imaging system or a component; it is the contrast at a given spatial frequency relative to low frequencies. [9]

It is now supposed that the input exposure is a one-dimensional sinusoidal distribution of the form shown in Figure 2.11. This may be defined as:

$$f(x) = a + b\cos(2\pi\omega x + \varepsilon)$$ (2.12)

where ω is the one-dimensional spatial frequency (or line frequency), and ϵ is

a measure of the phase. It will be shown that the output, or image, is also sinusoidal

with the same spatial frequency ω as the input, but with a change of amplitude, or

modulation. The ratio of the output modulation to the input modulation depends on

the spatial frequency, and turns out to be equal to the modulus of the Fourier

transform of the spread function. It is this ratio of output to input modulation that is

called the modulation transfer function, or MTF. Although this is now common

terminology, in older literature it may be described as the sine-wave response,

frequency response, contrast transfer, etc.

The input modulation is defined by:

$$M_{in} = \frac{f_{max} - f_{min}}{f_{max} + f_{min}} = \frac{b}{a} \qquad (2.13)$$

From the convolution relationship, the output is

$$g(x) = \int\int_{-\infty}^{+\infty} f(x - x_1, y - y_1)h(x_1, y_1)dx_1dy_1$$
$$= \int\int_{-\infty}^{+\infty}(a + b\cos(2\pi\omega(x - x_1) + \varepsilon))h(x_1, y_1)dx_1dy_1$$

Integrating with respect to:

$$g(x) = \int_{-\infty}^{+\infty} l(x_1)(a + b\cos(2\pi\omega(x - x_1) + \varepsilon))dx_1 \qquad (2.14)$$

where $l(x_1)$ is the line spread function. Using the expansion of cos(A - B) and

normalizing the spread function such that its area is unity, i.e.

$$\int_{-\infty}^{+\infty} l(x_1)dx_1 = 1$$

equation (2.14) may then be written as

$$g(x) = a + b\cos(2\pi\omega x + \varepsilon)\int_{-\infty}^{+\infty} l(x_1)\cos(2\pi\omega x_1)dx_1$$
$$+ b\sin(2\pi\omega x + \varepsilon)\int_{-\infty}^{+\infty} l(x_1)\sin(2\pi\omega x_1)dx_1$$

or

$$g(x) = a + b\cos(2\pi\omega x + \varepsilon)C(\omega) + b\sin(2\pi\omega x + \varepsilon)S(\omega) \qquad (2.15)$$

where

$$C(\omega) - iS(\omega) = T(\omega) = \int_{-\infty}^{+\infty} l(x_1)e^{-2\pi i \omega x_1}dx_1$$

The function T(w) is the optical transfer function, and C(w) and S(w) are its real and imaginary parts. The optical transfer function is the Fourier transform of the line spread function.

If $M(\omega)$ and $\phi(\omega)$ are the modulus and phase of the optical transfer function, defined by

$$M(\omega) = \sqrt{C^2(\omega) + S^2(\omega)}; \phi = \tan^{-1}\left(\frac{-S(\omega)}{C(\omega)}\right)$$

then $C(\omega) = M(\omega)\cos\phi(\omega)$; $S(\omega) = -M(\omega)\sin\phi(\omega)$.

Equation (2.15) now reduces to

$$g(x) = a + M(\omega)b\cos(2\pi\omega x + \varepsilon + \phi(\omega)) \qquad (2.16)$$

Equation (2.16) shows that the output g(x) is also sinusoidal, and has the same frequency as the input. The output modulation will be defined by

$$M_{out} = \frac{g_{max} - g_{min}}{g_{max} + g_{min}} = M(\omega)\frac{b}{a}$$

Thus the ratio of the output modulation to the input modulation is simply equal to $M(\omega)$ the modulus of the Fourier transform of the line spread function.

Since the area under the spread function has been denned as unity, the MTF will be normalized to unity at zero spatial frequency:

$$M(0) = \left| \int_{-\infty}^{+\infty} l(x_1) dx_1 \right| = 1 \qquad (2.17)$$

If the line spread function is both real and even, the imaginary part and the phase of the transfer function will be zero. In this case the real part of the transfer function, the optical transfer function and the modulation transfer function, will all be identical.

2.1.8 Measurement of the MTF by Sine Wave Methods

Methods based on the use of spatial sine waves are commonly used in the practical measurement of the MTF. Other types of method involve Fourier transformation of the measured line spread function, and the use of coherent optical systems, and will be discussed shortly. [10]

Suppose that a film is exposed to a one-dimensional exposure distribution, E(x), of the form:

$$E(x) = a + b \cos(2\pi\omega x) \qquad (2.18)$$

where ω denotes the spatial frequency and b/a denotes the modulation. After development the density or transmittance distribution of the image is scanned by a microdensitometer system. For a low contrast exposure the ratio of the output modulation to the input modulation give the modulation transfer factor for the spatial frequency, but the practice the microscopic curve is often used for all spatial frequencies.

The main problem associated with this method lies in the production of a spatially-sinusoidal exposure of known modulation. A relatively straight forward method is to photograph a variable area test chart of the type illustrated in Figure

2.12, using a cylindrical lens, a slit pupil, or other 'smearing' techniques. A scanning system coupled to a time –varying modulation of a slit exposure can also be used to achieve to required exposure distribution, and one such system is illustrated in Figure 2.13. A long narrow slit is image on to the film, and rotating polarizer with a quarter wave plate between them provide a time-varying sinusoidal intensity of known and adjustable modulation. In the arrangement shown in Figure 2.13 the imaged slit is scanned across the film using a mirror system and this particular method has the disadvantage that the lens is used at a range of angles. The relative merits of various types of scanning systems have been improved version of the apparatus shown in Figure 2.13 has been described. Defocused images of Moire patterns have also been used to produce an exposure distribution that is approximately sinusoidal.

IMAGE SCIENCE
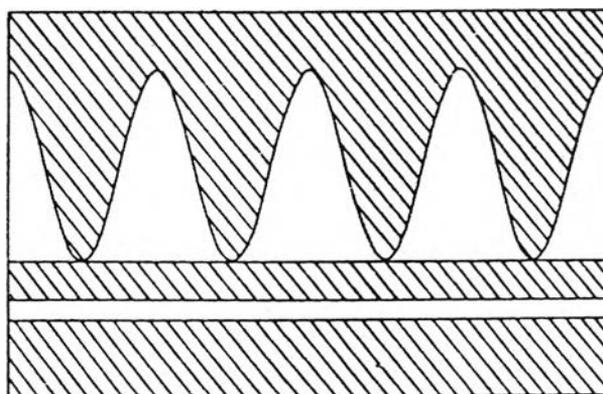
Figure 2.12 A variable-area sinusoidal test-chart.

The above methods of producing sinusoidal distributions are often used for the preparation of a large scale master chart, which can then be photographed, typically at a reduction of 25:1, when measuring MTFs.

For methods that involve imaging of variable-area or variable-transmittance chart, the measured MTF is that of the imaging lens-film-microdensitometer combination. These three components are combined linearity.

$$M_{film}(\omega) = \frac{M_{meas}(\omega)}{M_{lens}(\omega)M_{\mu dens}(\omega)}$$

(2.19)
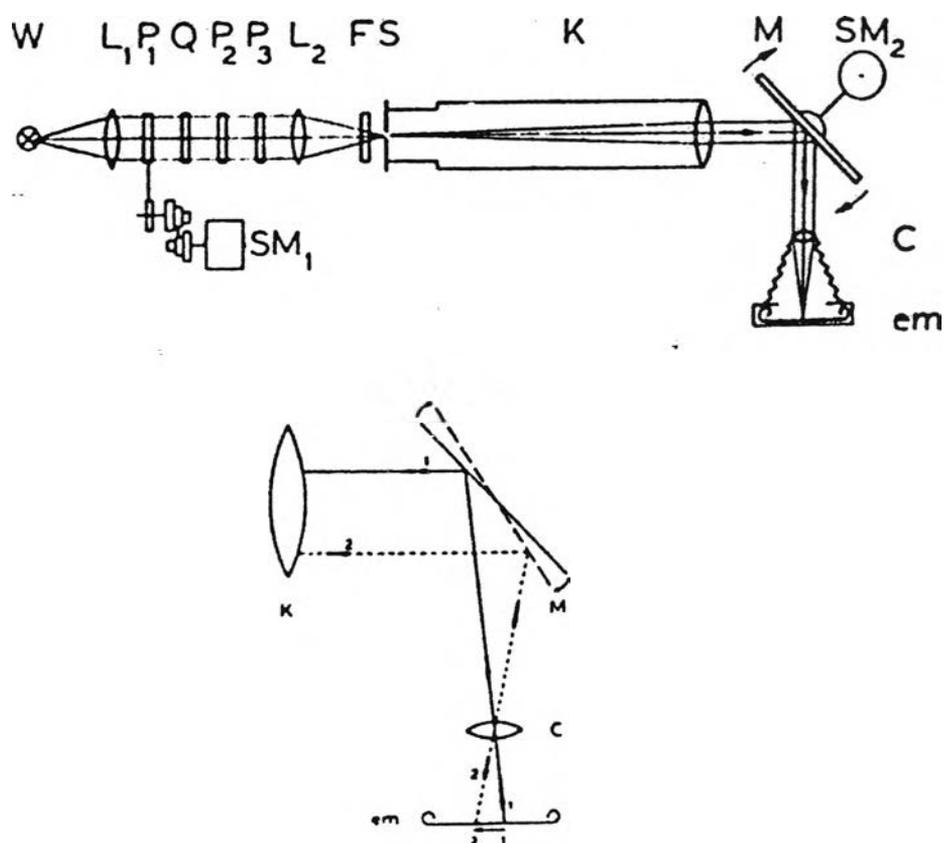
Figure 2.13 Apparatus for producing sinusoidal exposure distributions: W, tungsten lamp: L_1 and L_2 Lenses; P_1 rotating polarizer driven by synchronous motor SM_1; Q quarter wave plate; P_2 and P_3 polarizers with planes of polarization fixed at angles α and β to Q; S, entrance slit of the collimator K; M, Mirror rotated slowly by the synchronous motor SM_2; C, camera lens; em, photographic emulsion.

A correction based on equation (2.19) is only approximate for a number of reasons. The OTF of the imaging lens may not be unique, and will for example depend on the field angle. The transfer function of any imaging system depends on the plane of focus, and consequently for thick photographic layers the measured MTF depends on the numerical aperture of the imaging lens.

Interference fringes have also been used to produce sinusoidal exposure distribution. However it should be noted that if coherent light is used at the exposure stage, then the scattering that occurs within the layer will be linear in the complex amplitude of the radiation, and not in intensity, and in general the "transfer function" obtained using a coherent exposure is different from the incoherent MTF.

Due to the inconvenience of producing sinusoidal exposures, a square-wave chart of the type designed by Sayce is sometimes used, as shown in Figure 2.12.A square-wave "transfer function" $M_1(\omega)$ is measured using the square-wave exposure, where ω represents the fundamental frequency. A calculation base on the Fourier series of a square wave then gives an approximation to the true MTF:

$$M(\omega) = \frac{\pi}{4}\left(M_1(\omega) + \frac{1}{3}M_1(3\omega) - \frac{1}{5}M_1(5\omega)...\right).$$
(2.20)

A simple laboratory method of measuring the MTF may use a square-wave chart. The chart is imaged onto the film using a high quality lens with known OTF under the experimental conditions, and the resulting image is scanned in a microdensitometer, typically using a 2x500 μm slit and an objective of numerical aperture 0.25. A microdensitometer trace such as shown in Figure2.14 is obtained and the data is transferred through the macroscopic response curve to give the effective exposure square-wave transfer function (although of course this is not a real transfer function). The sine-wave response is calculated from equation (2.20) and this

response id divided by the transfer functions of the imaging lens and microdensitometer to give an estimate of the transfer function of the film alone.
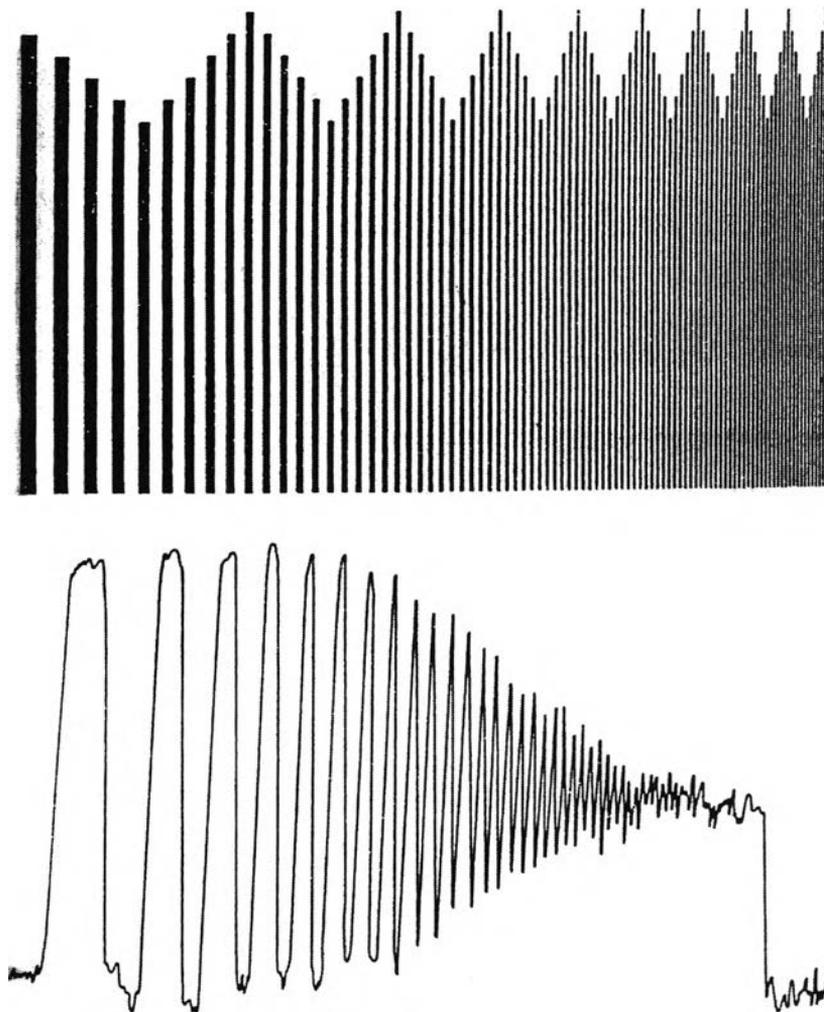
Figure 2.14 Upper: a modified Sayce chart. Lower: a microdensitometer trace of an image of a Sayce chart recorded on a medium-speed film.

2.2 Literature Reviews

Work and Kane have studied about developments in jet inks for textile printing. For the silk printed, they have announced commercialization and have in a beta

testing a set of 7 colors of acid dye inks especially chosen for use in the high-end designer market. Two versions will be available: one set is optimized for piezo printheads like those used in the Mimaki printer and one set is optimized for thermal ink jet printheads. A clear solution product is offered which enables the user to mix any combination of the 7 colors together and dilute to match any spot color in the wide color gamut provided. A silk fabric pretreatment solution is also being made available which is optimized for these dye inks and silk. Traditional steaming and washing is required to achieve the required color and durability. [11]

Inoue et al. proposed the measurement MTF of paper by sinusoidal test pattern projection. This method allows direct measurement of the MTF of any type of paper without special preparation. They modified sine wave method for measured MTF of paper. The sinusoidal test pattern is projected onto paper and reflection intensity distribution measured with a modified microdensitometer. The normal illuminating system of the microdensitometer is replaced with a special projection system fixed on the sample bed at an angle of 45°. This projection system consists of a chart holder with a sinusoidal test pattern film and a halogen lamp. The internal projection system is coated black to avoid the flare light. The function of this optical system is to project a uniform image of the sinusoidal test pattern in the chart holder onto the image plane. The projected image is focused only on a line on the sample bed, because the image is projected at and angle of 45°. Therefore, scanning was done on this focused line. The effective measurement aperture of the microdensitometer is 0.01 mm wide and 0.1 mm high. The results obtained by this measuring technique were stable. They introduced a model to predict reflection density based on the PSF (Point Spread Function) of paper from equation:

$$Dr(x,y) = -\log\{[T(x,y) * Rpsf(x,y)]T(x,y)\} - \log(Rr) \qquad (2.21)$$

$$MTF(\varpi) = \frac{1}{\left[1 + (2\pi d\varpi)^2\right]^{\frac{3}{2}}}$$ (2.22)

The prediction was obtained from Eq. (2.21). The normalized reflectance PSF Rpsf(x, y) was calculated mathematically as the other form of the paper MTF represented by Eq. (2.22). The exponential expression is

$$Rpsf(x,y) = \frac{1}{2\pi d^2} e^{\frac{-\sqrt{x^2+y^2}}{d}}$$ (2.23)

The result demonstrated that the predicted density in this model was approximately the same as the measured density in halftone printing. [12]

Inoue et al. have analyzing CTF of print by MTF of paper. This experiment introduced contrast transfer function (CTF) of printed. They find that the CTF of print, CTF_{print} (ω), can be expressed by a simple function of the MTF of paper:

$$CTF_{print}(\omega) = \left[1 + MTF_{paper}(\omega)\right]\frac{1}{2}$$ (2.24)

They measured CTF of print by sinusoidal test pattern contact method. A sinusoidal test pattern film was contacted onto sample paper, and this reflection intensity distribution was measured with a microdensitometer. The contrast for each spatial frequency can be easily determined by Eq. (2.25).

$$c(\omega) = i_{max} - i_{min}$$ (2.25)

$$CTF_{print}(\omega) = \frac{c(\omega)}{c(0)}$$ (2.26)

$$R = 10^{-D}$$ (2.27)

The CTF of print is given by Eq. (2.26). The illuminating system of the microdensitometer is the two light guides. The light source is a halogen lamp. The light guides are fixed at the near of the objective lens at an angle of 45°, from the

sample bed. Measurements were carried out by driving the sample bed with the sinusoidal test pattern film on the sample paper. The sinusoidal test pattern film on a sheet of sample paper was set on the sample bed in order to contact well. The emulsion side of the sinusoidal test pattern film contacted the sample paper. The sample bed was a black background. Readings were taken at 0.01mm intervals, namely, values obtained corresponded to the output intensity distribution. Because these recording data are reflection density, intensity (reflectance) can be obtained by Eq. (2.27). The contrast was calculated from maximum and minimum intensity of the output image using Eq. (2.25). The resulting CTF of paper was corrected using the system MTF. [13]

The effect of ink spread and optical dot gain on the MTF of inkjet image was discussed by Koopipat et al. [14] 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 MTF of ink image calculated from the Fourier transform of line spread function of one-pixel line image as shown in Eq. (2.28).

$$MTF_i(u) = \left| lsf_i(x)e^{-j2\pi u x} dx \right| \qquad (2.28)$$

where $lsf_i(x)$ is the line spread function of one-pixel line image, and u denote the spatial frequency. The line spread function of one-pixel line image is obtained from Eq. (2.29).

$$lsf_i(x) = 1.0 - \int t(x, y) dy \qquad (2.29)$$

where $t(x, y)$ is the transmittance of one-pixel line image.

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, they used Eq. (2.28) to calculate the MTF_i of one-pixel line image printed on a transparency that is in optical contact with those papers. Similar to 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. The MTF of ink image is caused by the ink spread but the MTF of print 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.