Engineering An Ink Jet Paper What's Involved?

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Abstract

People use paper to communicate ideas. Because customers prefer "plain" rather than specialty papers, ordinary copy paper is commonly used in ink jet printers. While most plain papers perform well in copiers and laser printers, performance varies considerably with ink jet printers. Why is this? Copy paper was originally designed for electrophotographic imaging systems, not aqueous, water-based ones. Physical properties for ink jet and xerographic papers differ considerably. Our paper focuses on the basic principles for engineering an ink jet sheet. Specifically, we deal with two issues: (1) What key image quality attributes are important and how are they measured?, and (2) How do we engineer a sheet to optimize them?

Introduction

People use paper to communicate ideas. Until recently, all aqueous ink jet printers required special paper to produce acceptable text, graphics and color. Because customers prefer "plain" rather than specialty papers (Bares & Rennels), ordinary copy paper is commonly used in ink jet printers. While most plain papers perform well in copiers and laser printers, image quality varies considerably with ink jet printers. Why is this? As we shall soon see, unfavorable ink/paper interactions are the actors responsible for poor performance.

Figures 1a-1d illustrate the dramatic differences one finds with ink jet images printed on plain papers (Lee & Winslow). The same digital image using the same dithering pattern was printed on four papers using a common HP Deskjet 500 printer. Figures 1a-1c were printed on commercial copy paper and Figure 1d on a specially formulated ink jet sheet. Contrast and sharpness variations are considerable. Note how uniform quality is when these same papers are imaged with a laser printer (Figures 1e-1h).

Figure 2 shows image quality evaluations of a representative set of commercial office papers that were printed on a 300 dpi laser printer and 300 dpi ink jet printer (Winslow & Lee). The results suggest that laser printing is essentially paper *independent* - there are no significant differences in image quality. Ink jet printing however, still depends on paper. Printer, ink, and paper form the three basic components of a printing system (see Figure 3) (Lee). The systems concept is important since overall performance is governed by its weakest component. Despite tremendous advances in ink jet technology, *paper still remains the weak link.*

Ink jet images are made up of small drops of water-based ink delivered ballistically to the sheet. Aqueous inks consist of many additives: e.g., water soluble dyes, humectants, biocides, buffers, and chelating agents. After reaching the surface, there is a delay before capillary flow forces it to migrate into the sheet. Delay time is a function of the hydrophobicity of the sheet. Water in the ink then starts to evaporate while diffusion and sorption wet the surface of the fibers (see Figure 4). After wetting capillary flow occurs until the drop has completely penetrated and is dry. During this phase, ink flow can spread laterally as well as down into the sheet. **Wetting**, **penetration**, and **spreading** are therefore the three major mechanisms making up the ink/paper interaction.

This paper deals with two topics important to ink jet printing. Part I discusses critical image quality attributes and their measurement. Part II reviews available techniques for engineering an ink jet paper.

Part I: Image Quality Attributes and Their Measurement

Attributes

For simple black and white printing, there are four fundamental attributes: (1) Sharpness, (2) Contrast, (3) Solid Noise, and (4) Tone Reproduction. Sharpness and contrast are most important with text, while all four play a role with graphics. Note that even though our discussion is limited specifically to black and white printing, the principles with minor extensions, apply to color as well.

Sharpness is a subjective term used to describe how distinct a picture is. A quick way to evaluate this is to look at how well edges are rendered in a simple image like a dot, or a line. Edges can appear blurred, ragged, or blurred and ragged (Hamerly). Figure 5 illustrates this with examples of sharp and ragged text. It turns out

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that our visual acuity is about ten times more sensitive to raggedness than to blur (Hamerly & Springer). Consequences of unsharp edges are feathered text, poor detail, and grainy halftones. *Key to sharpness is a dot with uniform circular spread leaving an abrupt transition between ink and paper.*

Contrast is a relative measure of the strength of an optical signal (see Figure 6). It tells us how black and white a print is. All things being equal, high contrast is better than low. *Key to contrast is minimal penetration into the sheet.*

Solid Noise is the non-uniform appearance of what should be a uniform field. Quantitatively, it appears as optical density variations in a solid or halftone where none should be. Solid noise refers to disturbance produced by an imaging system. *Key to low solid noise is a homogeneous sheet, i.e. a uniform distribution of fibers, fillers and size.*

Tone Reproduction is the ability to render continuous tone by modulating dot size. Theoretically, it can be derived from sharpness, contrast, and printer resolution (Gur & O'Donnell). Key to good tone reproduction is to do the above well.

Color image quality is a bit more complex and depends on the above attributes *applied to each process ink*. Unlike black and white printing which calls for a single pass of ink, color requires at least three.

If each ink achieves high chroma, then a large color gamut results giving a wide range of highly saturated hues. High sharpness yields good registration and therefore colors will be vivid and accurate. Two factors crucial to color quality are **drying time** and **ink bleed**. We

Figures 1a-1d. Dramatic variation in inkjet quality of plain papers printed with the Hewlett-Packard Deskjet printer.

have already alluded to the importance of ink/paper interactions in black and white printing. With color, ***ink/ ink interactions*** are even more important. This requires that inks be inert and not react with one another or the paper when they're laid down. Because dots are placed on top of dots, rapid drying is essential to prevent mixing and/or running of colors. Poorly engineered paper aggravates this problem.

In addition to the four, two **non-image** quality attributes should be considered: (1) drying rate and (2) waterfastness. In current water-based black and white printers **rapid drying**, while desirable, is not absolutely necessary. However, in color printers, they are a must in order to minimize multi-drop splatter, color image bleed, and the "running of inks". *Key to drying rates are short wetting delays and rapid absorption rates.* Even though **waterfastness** is not an absolute necessity, many customers feel it's important and desirable. In the typical office environment, this would include fastness to spilled liquids like coffee as well as highlighter pens. *Key to waterfastness are chemical mordants that bind the dye to the paper surface.*

Measurement

Sharpness is the single most important factor determining image quality (Lee & Winslow). The Modulation Transfer Function (MTF) (Granger & Cupery) is a quantitative measure of the acuity of an imaging system (see Figure 7). MTF is a formula that tells you how strongly a system modulates contrast at different spatial frequencies. Spatial frequency and resolution are equivalent.

Figures 1e-1h. Minimal variation in laser image quality of plain papers printed with the Hewlett-Packard Deskjet printer.

Think of high frequencies as high resolution, e.g. a very detailed image, and low frequencies as low resolution, or a very simple image. We can estimate an imaging system's MTF by examining a printed edge (Granger). With a vision system, we can digitize images of magnified edges (approximately 25X) (see Figure 8). Averaging pixel intensities across an edge gives us a profile which is plotted against distance. Differentiating this intensity profile yields a Line Spread Function (LSF). To estimate sharpness, we calculate it's variance (σ^2). Small σ^2 are desirable. They imply narrow LSFs or sharp transitions. Large σ^2 imply wide spread functions or equivalently, unsharp transitions. A *one-parameter Gaussian model using the variance of the LSF, serves as a good approximation of system sharpness (MTF)* (Granger).

U.S. Business Papers

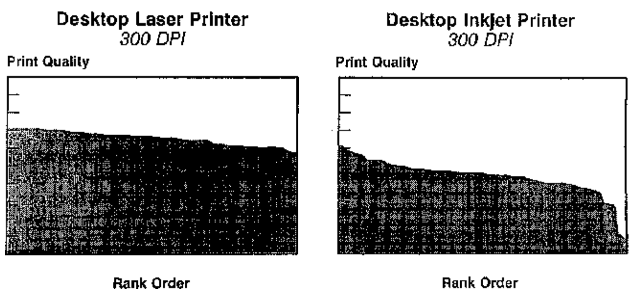

Figure 2. Print Quality evaluations of a representative set of commercial office papers printed using 300 dpi laser and ink jet printers.

Ink Jet System

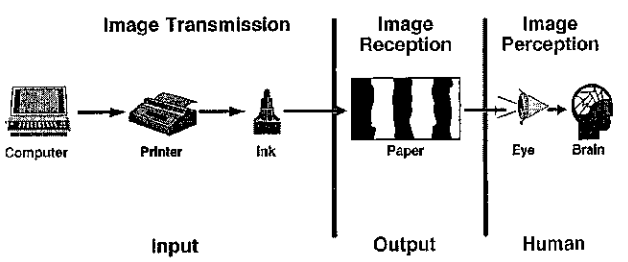

Figure 3. Printer, ink, and paper from the three basic components of an imaing system.

Image Generation in an Ink Jet System

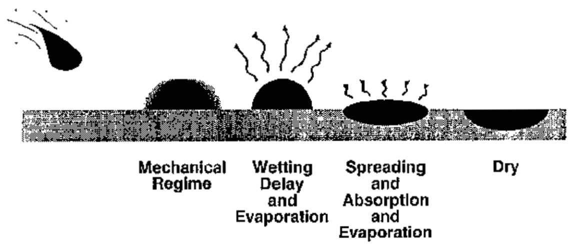

Figure 4. Image generation in a drop-on-demand, thermal ink jet printing system.

Contrast is easily measured with a variety of instruments, e.g. a colorimeter, spectrophotometer, or hand-held densitometer. In either case, two readings are taken. One of the unprinted sheet and the other over a solid area. A densitometer displays optical density (OD) units while the others report reflectance. *Subtracting paper density from solid density, i.e. D_s - D_p yields contrast.* Contrast for reflectance measurements can be calculated by taking common logarithms of their luminance ratio ($\log_{10}[Y_p/Y_s]$).

Sharpness

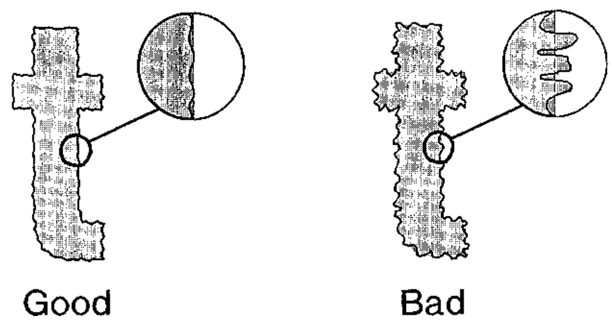

Figure 5. Sharpness or edge noise are terms used to describe how distint an image appears. Sharp edges are a common citerion.

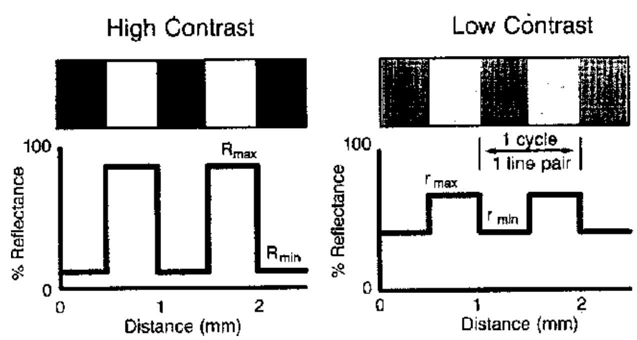

Figure 6. Contrast is a relative measure of the strength of an optical signal and is defined as the difference in an optical density of the light and dark areas.

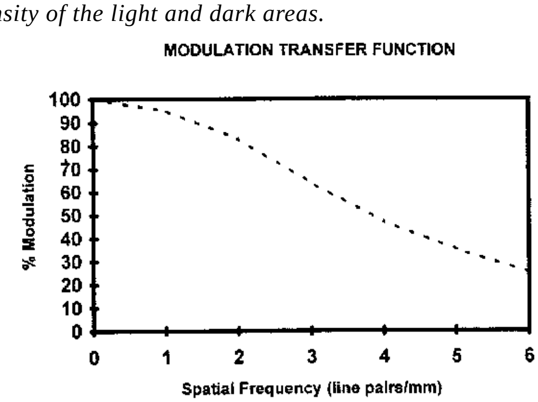

Figure 7. The Modulation Transfer Function is a quantitative measure of the sharpness of an imaging system.

Solid noise or mottle can be measured in many ways. We suggest a simple, yet effective measure which calls for a hand-held densitometer and the taking of about 30 random readings over a large solid area. Because variance will depend on the size of the sampling aperture, it is important that the aperture be relatively small (1-2 mm or less) compared to the dominant wavelengths (spatial) producing the major variations. Selwyn granularity G, defined as $2A\sigma^2$, where A is the area of the aperture and σ^2 is the variance in optical density *is one measure of the degree of mottle.* High values of G indicate significant mottle.

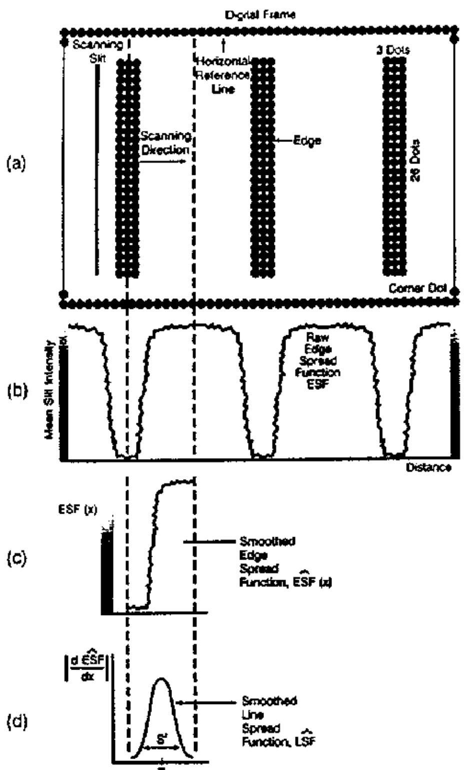

Figure 8. Schematic of edge capture (a), smoothing of Edge Spread Function (b), differentiation (c) and calculation of central moments of LSF (d).

Tone reproduction in conventional offset printing is done by fixing screen frequency and modulating the size of the printed dot. Current ink jet printers are binary, they either drop a dot or not. Consequently, the typical 1-bit ink jet printer is unable to vary its dot size or its density. A technique called dithering overcomes this. Dot size is modulated with a *larger* halftone dot made up of many small dots into an array, e.g. 3 horizontal by 3 vertical dots. Solid areas would be printed by firing all 9 dots in the array with none being fired for a pure white. Given a 3x3 matrix, 9 shades of grey can be rendered. The array size determines the nominal levels of grey. At this point, we make a distinction between *nominal* and *actual* performance. *Nominally*, this system is capable of generating 9 shades of grey. However, the *actual* number can be considerably less. For a given printer resolution, it depends on two key things: (1) sharpness (MTF), and (2) dot gain, i.e. how much a dot spreads beyond it's ideal size. Increasing dot gain even with high sharpness, reduces tone since adjacent dots begin to fuse. Poor sharpness reduces tone by imparting an undesriable grain to halftones. *A simple measure of tone is to calculate the ratio of actual to nominal grey levels.*

Part II: Engineering An Ink Jet Paper

Why do we need to engineer paper specifically for an ink jet printing system? *Because image quality is paper's greatest contribution to system performance.* Currently, "plain" paper is the weak link. Since it can make or break a system, we have to pay attention to how its made. Even though print quality can be improved by modifiying the ink, the physics of current drop generation technologies place severe constraints on ink rheology and chemistry. Also, consumer and environmental issues limit the choice of dyes, solvents, and additives. While there's been a strong effort to make the ink jet process fully paper-independent, to date, there is no viable alternative other than "solid" ink jet.

Recall that wetting, penetration, and spreading were the three major mechanisms making up the ink/paper interaction. Figure 9 illustrates these within the MTF construct. Under the ideal condition shown in Case A, we would have rapid wetting, minimal penetration (high density) and no spread (no dot gain and high sharpness). What results is a high contrast, sharp image, or a flat MTF. Case B is like A except the ink penetrates too much. Despite poor contrast, its still sharp , and MTF is just shifted down. Case C is the other extreme. Here we have minimal penetration with excessive spread and so we have high contrast, but poor resolution, hence a steep MTF. While we strive for A, more common is D, where we get both penetration and spread. These systems will be plagued with reduced contrast, reduced resolution, and MTF's mirroring Cases B and C.

Ink/Paper Interaction of Imaging System

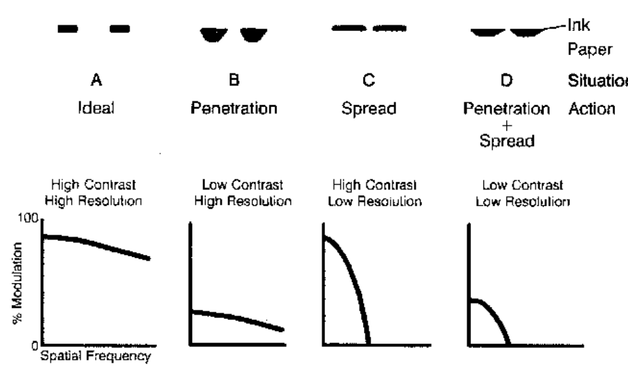

Figure 9. How ink/paper interactions degrade image quality. Degradation of MTF from excessive ink penetration & spread.

Think of paper as a two-part structure made up of a body and a surface. The surface is paper's most important quality—the ability to transfer information. The body does three things: 1) support the surface, 2) provide strength, and 3) serve as a medium for optimizing the performance of additives. Armed with this concept, there are three key factors for engineering paper: (1) selecting and preparing materials, (2) placing materials in the sheet, and (3) finishing. Let's see how these strategies are used to optimize image quality.

*Key to **sharpness** is uniform volume, placement, and spread of the ink.* While the first two are machine dependent, the last isn't. To minimize wicking in uncoated papers, pigments such as $CaCO_3$, TiO_2, and ATH are added at the wet end and/or size press. Pigments tend to break up the random flow of ink along surface fibers and therefore improve sharpness. While they weaken the sheet, they fill voids minimizing ink penetration routes. Fillers also improve opacity and whiteness, thereby reducing showthrough and improving contrast. However, uniform surface dispersion, machine retention, retention aids and particle size determine how effective this treatment is. Besides pigments, surface starch and various synthetic sizing agents such as AKD (ketene dimers) and alkenyl succinic anhydride (ASA) have been applied at the size press to control unwanted ink migrations. Unsized wood fibers have a strong affinity for water. Sizing agents have low surface energy which they impart to the fiber, thereby reducing the fiber-water attraction and slowing the rate of penetration and spread.

*You improve **contrast** by minimizing ink penetration and to a lesser extent, lateral spread.* Contrast is the difference in optical density between the unprinted sheet and a solid area. So you improve it by either making the sheet whiter or making the printed area darker, or both. Ways to improve sheet whiteness include using different blends of fiber, tinting with blue dyes, additional bleaching, or addition of pigments and fluorescent dyes. While these promote contrast, improvements are modest. This is because increasing sheet reflectance translates into a small change in optical density. Most plain papers achieve adequate whiteness. A cheaper and better approach is to improve print density. In uncoated papers, sizing is used to make the body (added at wet-end) and the surface (added at size press) of the paper more water repellent. Internal sizing slows down the ink penetration rate and for the most part works well with the current generation of black and white ink jet printers. Surface sizing agents such as ASA and AKD, increase hydrophobicity by filling in voids and sealing small holes in paper.

Color imaging calls for a different strategy. For color printing where rapid absorption and drying time are required, coatings are applied. Coating provides an adequate pore volume so as to hold the ink as close to the surface as possible. High surface area, hydrophyllic minerals like silica are typically used and being transparent, increase the color saturation and brilliance of the trapped dyes. With this approach, highly saturated, high contrast colors can be achieved with minimal color bleed. However, these sheets do not "feel" like plain paper. The recent introduction of the H.P. Deskjet 1200C however, demonstrated that coated papers were no longer necessary to achieve acceptable print quality. By formulating a pigmented black along with yellow, magenta, and cyan dyes, crisp colors were possible using plain paper. Even though more vivid colors are produced with coated papers, the HP 1200C is a significant breakthrough in water-based color ink jet printing on plain papers. And the key technology which minimized ink/ink interactions was the pre-heating of the sheet prior to printing and the use of a pigment black instead of a process black (3 dyes).

*We minimize **solid noise** by forming a homogeneous sheet, i.e. uniformly distributing fiber, fillers and sizing agents.* This minimizes variations in localized surface chemistry, formation, pore structure, coating, and mass density. Mottle occurs because of differential absorption of ink in localized regions across the sheet. Even though this effect is more visible in uncoated papers, it occurs in coated papers too. For uncoated and coated sheets, good formation produces uniform ink absorption. Given a more uniform mass distribution, optical density variations are minimized. Good formation also dictates how uniform surface applications will be. Poorly formed paper contributes to poor and uneven coating coverage. Since **tone reproduction** depends on all of the above, optimizing them will ensure good results at any printer resolution.

Absorption rate can be controlled either chemically or physically. Internal and surface sizing chemicals can be used to control this. Physical solutions include for example, heating elements. The Deskjet 1200C uses a heater to accelerate drying time and minimize cockle. **Waterfastness** is a challenging issue with aqueous inks. The strategy calls for a chemically reactive mordant to bind the dyes to the paper's surface. Cost issues however, make this solution impractical. This area is fertile for developing new strategies for placing dye-capture agents in the sheet.

Typical Output Response for
Inkjet Printer-Paper Imaging System

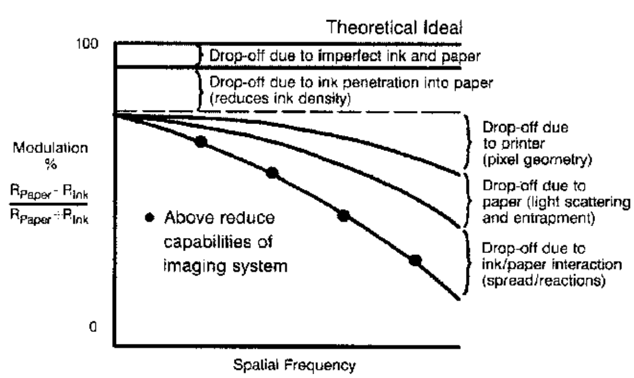

Figure 10. How ink/paper interactions degrade image quality. Note the strong role plays

Conclusion

Substantial growth is expected in ink jet printing. While early forecasts called for growth in monochrome ink jet printing to be in the office and color in engineering and graphic arts, this distinction will probably blur as the technology improves and prices drop. Forces behind this push are higher speed, higher resolution, lower cost, ability to use plain paper, color, and better image quality. Figure 10 uses the MTF framework to illustrate the large opportunities for improving the weak link - paper. Degradations in system MTF can be partitioned into several sources. Of the five identified, paper plays a significant role in four. Of the four, it is dominant in three: penetration, spread, and light scattering. How we engineer the sheet will determine net system performance, i.e actual versus nominal. Engineering the sheet to limit ink penetration into the body of paper, minimize lateral spread, and improve drying time, are the keys to optimizing performance.

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