Effect of Ink Drop Coalescence on Print Quality in Solid Ink Printing

Shu Chang and Peter Paul
Xerox Corporation, Wilson Center for Research and Technology
Webster, New York, USA

Abstract

In ink jet printing, coalescence of separately deposited drops can occur on some media surfaces.[1,7] These drops will move towards one another or combine into larger drops. The coalescence of these drops can degrade the print quality. Coalescence has been described with a 3-parameter model by fitting the parameters to microscopic measurement of the drop motion.[2] In this work, we incorporate this 3-parameter model into a solid ink printer simulation and examine the impact of coalescence on print quality. We find that coalescence causes "pairing" of the pixel columns in the cross-process direction (perpendicular to direction of paper travel) and line breaks in the process direction. For streaks that are caused by the interlacing process, coalescence also further degrades the streaking appearance. We will provide possible physical explanations to drop coalescence and how it can be minimized resulting in improved print quality.

Introduction

In ink jet printing, nozzle-to-nozzle spacing and, if interlacing is used, interlace patterns determine the positions of drops (or pixels) in the cross-process direction (perpendicular to direction of paper travel). For the process-direction, the ejection frequency and surface speed of the image receiver determine the drop positions. Errors in pixel placement can come from print head nozzle spacing inaccuracies, ejection miss-directions, and print head move-errors in interlacing. If an intermediate receiver is used to transfer images to paper, transfer and fixing processes can also introduce errors in drop positions. For a process using an intermediate receiver, coalescence of solid ink drops can occur on the intermediate receiver. In addition to mechanical errors, coalescence can further modify the drop placement from a physical process. Any misplacement of pixels, including coalescence effects, will lead to degradation in print quality.

Previously, N. Jones et. al.[1] have studied coalescence of aqueous ink jet drops on different media. In their work, Jones et. al. proposed the use of mottle to measure the print non-uniformity induced by coalescence.[1] Jones et. al. showed that the degree of ink drop coalescence depends on the receiving substrate surface properties and the rate of drop stabilization. The rate of stabilization was defined by these authors as the rate at which the drop is absorbed into the substrate. In this work, we examine coalescence of solid ink drops on a non-absorbing substrate and its effect on print quality, particularly, its influence on interlace streaking appearances.

We simulate the coalescence effect on print quality in a solid ink printer simulator. We utilize the coalescence effect determined from previous microscopic measurements of ink drops on an intermediate receiver. We examine the impact of coalescence on the interlacing streak defect.

3-Parameter Coalescence Model & Its Implication

The coalescence characteristics used in our printer simulator are from an earlier work by S. Wang and P. Paul.[2] Wang and Paul generated pairs of drops in the cross-process direction with predetermined drop distances ranging from 0 to 2 i_p , where i_p is the diameter of an isolated ink drop measured on paper, and measured the output center-to-center distance of the pairs. Figure 1 depicts the outcome of Wang and Paul's measurement (units are normalized to i_p). In figure 1, the coalesced pair distance (y axis) is depicted against the input pair distance (x axis). The black line in figure 1 shows the situation where the output distance equals the input distance (line of no coalescence). Wang and Paul's measurement (red data line), however, deviates from this one-to-one correspondence except at pair spacing greater than i_p . From their experiment, Wang and Paul identified three distinct regions: 1) less than the drop diameter on the intermediate receiver ($< i_d$, region I in Fig. 1); 2) between diameters of the drop on the intermediate and on paper ($>i_d$ and $< i_p$, region II), and 3) greater than the drop diameter on paper ($>i_p$, region III). Both regions I and II are considered regions of coalescence because of the smaller output distances relative to the input distances.

Wang and Paul constructed a 3-parameter coalescence model, defining three linear equations for regions I, II, and III in figure 1, respectively.

$$d_{out}(d_{in}) = \begin{cases} \left(\dfrac{c_0}{i_d}\right) \bullet d_{in}, & \text{for } d_{in} \le i_d \\ \left(\dfrac{i_p - c_0}{i_p - i_d}\right) \bullet (d_{in} - i_d) + c_0, & \text{for } i_d \le d_{in} \le i_p \\ d_{in}, & \text{for } d_{in} \ge i_p \end{cases}$$

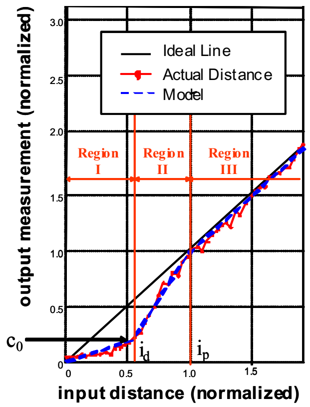

Figure 1. Measurement ink drop coalescence.

The three parameters in their model are the i_d, i_p and c_0, with i_d being the drop diameter on the intermediate drum, i_p the drop diameter on paper, and c_0 the break point between equations (1) and (2) (the output distance for drops that just touch on the drum).

The three parameters control the coalescence behavior of the drops. First, let us examine c_0. For a given i_d, c_0 brings the lines in regions I and II to either below or above the ideal line. Figure 2 sketches the 3-parameter model in regions I and II for a number of c_0 values (c_0, c_0', c_0" and c_0"'). The c_0's and the given i_d mark different break points (A, B, C, and D) and determine different slopes for lines in regions I and II. When c_0 is less than i_d, such as at points A and B, the output distances on the intermediate are less than input spacing from ejection in both regions I and II. Drops have coalesced. Since c_0' is closer in value to i_d than c_0, the drop pairs following lines defined by B will coalesce less than the drop pairs defined by A.

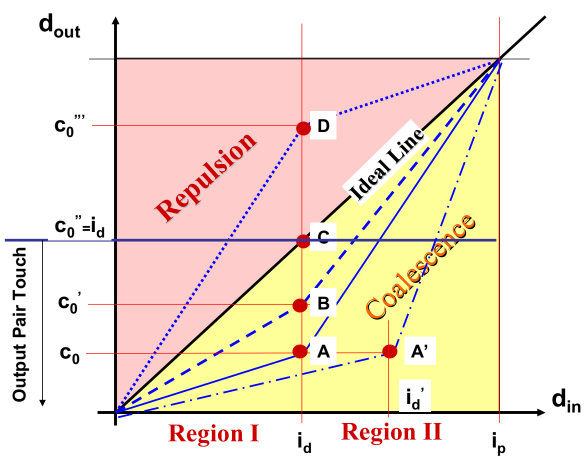

Figure 2. Roles of c_0 and i_d in the 3-parameter model

Since c_0" equals i_d (point C), the two drops do not coalesce and the three linear equations converge into a one-to-one input-output distance relationship (the ideal line). The blue horizontal line defined by c_0" also marks the boundary below which the output drops are touching, or aggregates. Within this boundary, region I has only aggregated output drops while Region II consists of output drop pairs of both aggregates and non-touching drops.

When c_0 become greater than i_d as represented by point D, the drops would repel each other since the output pair distance is larger than the input pair distance.

Second, let us now turn our attention to the drop diameter on the intermediate. For example, points A(c_0, i_d) and A'(c_0, i_d') in figure 2 also define different coalescence behaviors. The input-output linear equations defined by point A are closer to the ideal line than the relationship derived by point A', thus point A describes a smaller movement of the drops than does point A'. For a given c_0, larger drop diameters on the intermediate result in greater coalescence of the drops. Also, larger drop diameters on the intermediate imply more extended Region I, which means more aggregated drops.

Lastly, in contrast to c_0 and i_d, drop diameter on paper ip defines the extension of regions I and II. It does not impact the drop's coalescence or repulsion behaviors. However, ip is important since a larger ip will result in movement of ink drops over a larger area.

Overall, we expect more deviation from the ideal line will contribute to greater deterioration on the image appearance. A large paper drop diameter ip, a large intermediate receiver drop diameter i_d and a c_0 much less than i_d should result in a significant impact on print quality.

For two drops on a receiver, the interaction between them is determined by the attraction or repulsion between the drops and the adhesion that "pins" the drops to the intermediate surface. These forces could be van der Waal (attractive, short range), capillary (attractive, short range), or electrostatic (attractive or repulsive, long range) in nature. The "pinning" depends on the contact area of the drops to the intermediate surface, the physical state of the drops (solid or liquid, if liquid, at what viscosity), the drum surface properties, and the surface roughness. In the paper of Jones et. al., the physical state of drops is described by the rate of ink absorption into the media1. Here, the physical state of drops is reflected in the rate of solidification: the phase change of liquid ink drop into solid. For coalescence at short input distances, such as in region I, van der Waal and capillary attraction will dominate. Minimization of surface energy and the adhesion of drops to the intermediate will determine the final shape of drop agglomerates. For larger input distances, such as in region II, the forces are likely to be electrostatic. Electrostatic force and adhesion are likely to determine the final drop placements. Repulsion of two drops could occur if charges on the two drops were the same sign. For repulsion, electrostatic force and adhesion are likely to be responsible for drop placements in both regions I and II.

Interlace Defects

After describing the effect of coalescence, let us now examine the effect of coalescence on print quality. From the grey scale values of the images, Jones et. al. previously used a quantity called mottle to measure the influence of coalescence.[1] For our study here, we choose the spatial variation of L* (the perceived optical density as a function of positions on paper in units of CIELAB luminosity) in the frequency domain since we are interested in the impact of coalescence on streaks caused by interlacing errors.

The interlacing process is a pixel "filling" in the cross process-direction (direction of print head travel, perpendicular to direction of paper travel) to increase cross process direction print resolution beyond the native resolution inherent in the print head's cross process direction nozzle spacing. For example, if the desired print addressability is ten times greater than the inherent nozzle spacing, the print head can eject a line of drops in its initial position then move 1/10 of a nozzle spacing and eject another line of drops, then again move 1/10 of a nozzle spacing and eject another line of drops, etc… up to a total of ten positions to create the 10x greater print addressability and fill the entire space in 9 moves. Pixel columns 1, 11, etc… are printed in the initial position, columns 2, 12, etc… are printed after the first move, and so on on subsequent moves. Much more complicated move sequences are possible. The move sequence is often referred to as the "interlace" pattern.

Interlace defects occur when the print head does not achieve the desired position on subsequent moves due mainly to mechanical positioning errors. In the example above, if the print head moved too far on move 2, there would be a "gap" between pixel columns 2 and 3. The "gaps" will have a periodicity of the nozzle spacing. The luminosity will be higher where there is a larger gap than when the drop spacing is closer. This change in luminosity will be periodic with period equal to the nozzle spacing (at ~1/d cycles/mm frequency where d is the nozzle spacing in mm). When this move error is significant, the variation in luminosity will become perceivable and will give a streaky print appearance. In operation, the printing system will have move errors on all moves of the print head during interlacing. It can be shown that irrespective of the amplitude of the errors on the moves, the luminosity variation in the print due to the interlacing errors will always have a period equal to the nozzle spacing period (for uniformly spaced nozzles).

Simulation Details

Our pixel placement simulation is a Matlab-based model that maps pixels of a digital image, incorporating random ejection direction variations and print process errors, into positions and masses of ejected drops on paper, as well as the luminosity of the final image.[3] The interlace streaks in this work were created by print head move errors in the second pass of an interlacing process.

To include the coalescence effect into the simulation, we have divided 1" × 1" halftone images into smaller cells for more efficient computations. The pixels are ejected according to their sequence as in a typical Xerox solid ink printer. For each incoming pixel, the simulation looks for a nearest neighbor drop among drops already deposited in the nearest cells (eight of them). When the nearest drop is identified, the new pixel's position is modified according to rules of the 3-parameter model.

The input to our simulation is a uniform contone gray level patch halftoned using a stochastic screen to a binary image. The printer simulation converts the binary images to a positional variation of L* with microscopic detail as follows:

1) Mapping the 1"x1" digital image into positions of centers of ejected drops.
2) Modifying the drop centers to include other physical influences such as random direction variation of ejected drops and coalescence of drops. For simplicity, we have assumed that the coalescence is isotropic and used the same parameters in both cross process and process directions.
3) Creating an ink mass distribution around each pixel center.
4) Converting the mass distribution to a microscopic L* distribution, whose values are determined using an empirical model advanced by H. Mizes[4] based on the work of J.S. Arney and M. Katsube,[5] which incorporates attenuation of light in the paper (Yule-Nielsen effect).

For this work, all simulations include an isotropic 4µm 1-sigma position error per each drop ejection using a normal distribution.

Measurement of Interlace Errors

In the case of an interlace move error in one of the N moves, streaks reflecting the 1/d cycles/mm drop-to-drop gap variation and its harmonics appear in the L* variation amplitude vs. frequency spectrum. We transform the resulting L* spatial variation from the simulation into frequency space and obtain L* variation amplitude as a function of frequencies of cycles/mm.

Figure 3 displays a result of this process. Figure 3a shows L* amplitude variation for a 25 µm print head move error case (blue line) and that of the no error case (red line) for a digital gray level of 175 (0 = dark, 255 = light). The simulation shows a broad feature from zero to trailing at ~5/d cycles/mm. This broad-band noise is from the structure of the halftone screen. It is stochastic and therefore it is distributed over all frequencies. Comparison between the blue and red lines shows that under the same condition (no coalescence here; however, with coalescence, both behave the same), broad band noise features from the two cases are roughly identical. The pronounced differences are peaks at ~ 1/d, 2/d, 3/d, 4/d cycles/mm, reflecting the 1/d cycles/mm streak and its harmonics created by the error in interlacing.

We use the difference between the two spectra for our quantitative analysis of the interlace streak, or the ΔL* variation. For example, to get the L* variation difference at 1/d cycles/mm for the case in figure 3a, we subtract the two frequency spectra. Figure 3b shows the result of the subtraction. The height of the peak at 1/d cycles/mm gives us the magnitude of the streak. The harmonics of the 1/d cycles/mm streak are assumed to be much less perceptible than the fundamental due to the human VTF roll off at high spatial frequencies6 and therefore are not used in our study.

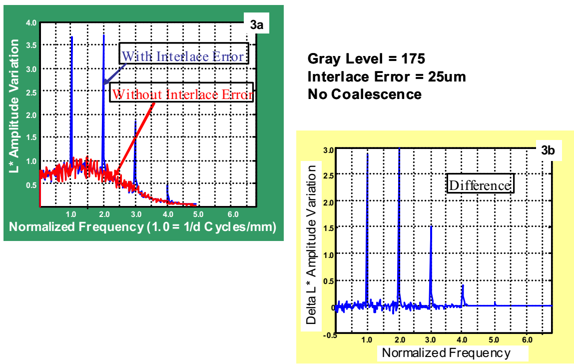

Figure 3a. Comparison of L variation amplitude in the x-direction frequency space for with interlace error vs. no error. 3b, Difference between the erred and no error cases that provides the measurement of the interlace error.*

Coalescence and Its Effect

No Interlace Error

Figure 4 shows the impact of coalescence on L* amplitude variation with no interlace error for a 175 digital gray level halftone patch. The blue data is from simulation of the L* halftone patch with no coalescence. The red data is the simulation of L* halftone patch with coalescence. When there is no interlace error, the effect of coalescence is reflected in increased noise in comparison to the without coalescence case. In addition, the coalescence appears to introduce a peak at 3/d cycles/mm.

This 3/d cycles/mm streak indicates "pairing" of pixel columns and is caused by writing pixels in multiple moves of the print head under the influence of the 3-parameter coalescence model. The harmonic that is excited by the pixel "pairing" is a function of the specific interlace sequence chosen. The tone due to pairing of pixel columns, however, is assumed not perceivable by observers since it is at a high spatial frequency where the human VTF rolls off.[6]

In the y-direction, we observe a similar enhancement on the broad-band peak, however, without the 3/d cycles/mm streak since the interlacing process does not create streak defects in this direction.

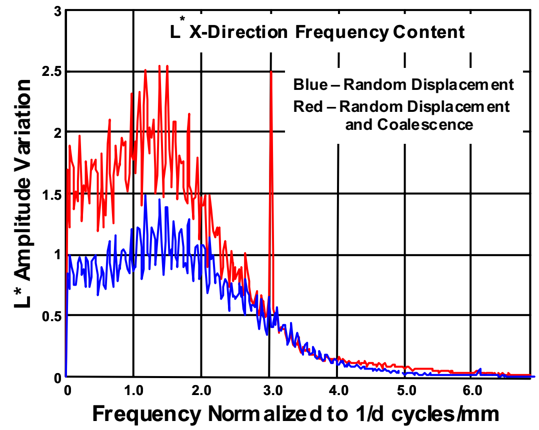

Figure 4. L variation amplitude in the x-direction frequency space. The 3-parameter coalescence produces an enhancement in the broad band noise and a streak at 3/d cycles/mm.*

Parameter c_0 and Interlace Streaking

The impact of coalescence as described by the 3-parameter model on interlace error induced streaks is depicted in figures 5 and 6. Figure 5 shows the effect of c_0 on the interlace error induced streaking. In figure 5, the diameter of the drop on the drum (i_d) and the diameter of the drop on paper (i_p) are held constant. The images used for interlace streak measurement in figure 5 have a gray level value of 151. Figure 5 plots the amount of the interlace move error on the x-axis of the plot and the amplitude of the change in luminosity, ΔL*, at the interlace streak's fundamental frequency of 1/d cycles/mm on the y-axis of the plot. In figure 5, the magenta squares depict simulated ΔL* variation for different interlace errors when there is no coalescence. The orange triangles, cyan diamonds, green squares and black circles are simulations for various levels of c_0. If coalescence affects the interlace-streaking appearance, from our discussion of c_0 and figure 2, smaller c_0 values cause greater coalescence in pixel placement, we should observe a larger impact on the streak from $c_0 = 0.62\ i_d$. Shown in figure 5, the 0.62 i_d coalescence parameter (orange line) does produce the most deviation from the no coalescence case, as expected. Also, as we discussed earlier, a value of c_0 closer to i_d generates a closer correspondence to the ideal pixel placement. From a comparison of the 0.92 i_d (green line) data with the no coalescence result (magenta line), we see that when c_0 approaches i_d, the effect of coalescence diminishes. A value of $c_0 = 1.08\ i_d$ describes a repulsion between the drops. It is also close to the i_d value and it has minimal impact on the interlace streak. We did not investigate the repulsion cases further since it has not been observed experimentally in the Xerox solid ink printing process.[1,3,4]

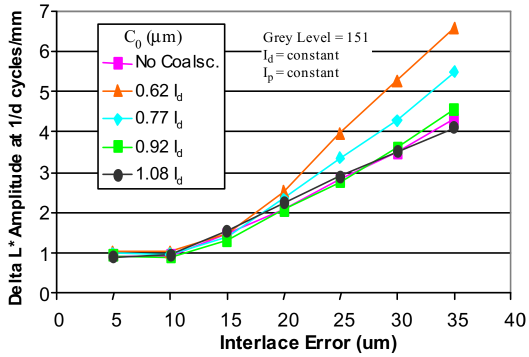

Figure 5. Effect of the coalescence parameter c_0 on the ΔL perceptibility of the interlace streak at 1/d cycles/mm. Coalescence increases the perceptibility of the interlace error induced streak.*

Also note that for the interlace error region of less than 20 µm, the coalescence has little additional impact on the streaking amplitude. In this region the interlace move error dominates the streak level, not the coalescence. For larger interlace errors coalescence increases the streakiness.

Parameters i_d and Interlace Streaking

Figure 6 shows the impact of i_d on the interlace defect. Figure 6 displays the ΔL* streak amplitude at 1/d cycles/mm as a function of different values of c_0 for various drop diameters on the drum, i_d. The interlace-move error in this example is 25 µm and it is for a 151 digital gray level patch. The blue diamonds, magenta squares, and orange triangles represent various levels of i_d. The red dash line at 2.88 is the interlace streak ΔL* amplitude at 1/d cylces/mm for the same image when there is no coalescence.

Let us look at the large drop diameter case (orange triangles) first. Figure 6 shows, for i_d = 1.31 i_{dnom}, a significantly large ΔL* amplitude at c_0 = 0.625 i_{dnom} and this ΔL* diminishes to the non-coalescence ΔL* value (2.88) when c_0 approaches 1.31 i_{dnom}. For the medium-sized drop, i.e., i_d = 1.0 i_{dnom}, the magenta squares displays a similar trend, however, at a much lower magnitude. When i_d becomes small, say 0.77 i_{dnom}, the ΔL* is relatively independent of the coalescence parameter c_0, as shown by the blue diamond symbols.

Results in figure 6 indicate that with large drop diameters on the drum, coalescence can significantly impact the interlace streaking. However, when the drop diameters on the drum become small enough, coalescence has little or no effect on the interlace streak appearance. These results are consistent with our expectations.

For i_d = 1.31 i_{dnom} and c_0 = 0.625 i_{dnom}, we have reproduced the case of point A in figure 3. Point A creates a large region I, a large region for forming agglomerates and great deviation from ideal pixel placement. In this case, we expect significant impact on image quality. The case of i_d = 1.31 i_{dnom} and c_0 = 0.625 i_{dnom} in figure 6 produces a streak amplitude more than 2.5 times greater than the no coalescence case. For i_d = 0.77 i_{dnom}, conditions for point B in figure 3 emerges. At point B, region I is small and there are not many agglomerates and a reduced deviation from the ideal line. In this case, we do not expect much degradation in the image quality. This is depicted by the blue diamonds in figure 6.

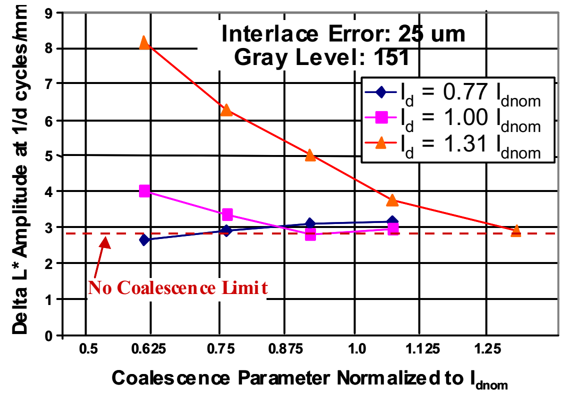

Figure 6. Impact of i_d on the interlace streak amplitude. Larger i_d gives more impact.

Conclusion

In the Xerox solid ink printing process, there are two places ink drops can collapse into each other: on the imaging drum or during the process of transferring from the imaging drum to paper. Coalescence of drops studied in this work is the process of "collapsing" on the imaging drum. The driving force is intrinsic and the direction of the drop motion is determined by the energy minimization. The 3-parameter model is an approximation of the drop collapsing behavior on the imaging drum.

The effect of coalescence on the print quality, such as streaks caused by the interlaced printing, depends on how much the drop collapses. The c_0 and i_d parameters in the 3-parameter model have significant effect on the coalescence and thus the image quality. Further deviation from the one-to-one input-to-output drop distance relationship creates larger coalescence, and consequently, interlace error induced streaks of larger amplitude. Delivering smaller diameter drops on the imaging drum can minimize the coalescence effect on print quality. Coalescence with relatively small drop diameters on the drum does not significantly change the amplitude of the 1/d cycles/mm streak defect caused by interlace errors if interlace errors are small.

References

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Biographies

Shu Chang is a research staff member at Xerox Wilson Center for Research and Technology. She completed her Ph.D. in Materials Science at the University of Minnesota in 1988. Her work has covered a variety of fields including semiconductor surfaces and electronic properties at metal/semiconductor interfaces, adhesive and cohesive properties of toners, colloidal science, liquid and powder toner xerographic processes, printing on unusual substrates, textile printing, image permanence, as well as solid ink jet printing. Shu Chang has over 45 publications and 10 patents.

Peter Paul is a research staff member at Xerox Wilson Center for Research and Technology. He completed his Ph.D. in Electrical Engineering at Case Western Reserve University in 1994. His work has focused on image processing, signal processing, control systems, and mathematical modeling and simulation of complex systems. His application areas have included robotic systems, radar and communications systems, and printing systems. At Xerox his work has been in job integrity monitoring, process controls, pixel registration controls, image quality modeling and simulation, and color sensing and controls.