Methods to Mitigate Dot Position Error Amplification of Phase Change Inks

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Abstract

Each new printing product needs to have an increase in performance over previous products. As customers continue to demand higher speed printers with higher resolutions, printheads need to have higher jetting frequencies, higher jet densities/number of jets and smaller drop masses to meet these demands. These performance increases have created an issue called dot position amplification. Dot position amplification is the increase in color-to-color misregistration when a secondary color is deposited. This issue is caused from an increased delay time between the deposition of secondary pairs of drops to the same location and a decrease in time for solidification because of drop size reduction. This increase in delay time and decrease in solidification time is enough for the first drop to freeze before the second drop is deposited. The second drop appears to fall to one side and increase the color-to-color dot position error. This paper presents a method to mitigate this amplification by intentionally misregistering the colors.

Introduction

The most common printing architecture for ink jet printers is direct printing. Within this architecture a small head shuttles back and forth over the width of a page directly depositing ink drops on the media. This shuttling continues down the page as the media is passed underneath the printhead. In a second ink jet printing architecture, known as offset printing, the printhead images onto an intermediate transfer drum, see Figure 1. After the entire image is deposited on to the transfer drum, the media is brought into contact with the drum through a high-pressure nip and the image is transferred onto the media.[1]

Xerox employs the offset printing architecture in combination with a phase change ink in the Phaser 8400® printer. This ink used for the Phaser 8400® is specially formulated and engineered to meet specific constraints including viscosity at jetting temperatures, specific visco-elastic properties at drum-paper temperatures, durability at room temperatures and color fastness. The ink is placed into the printer in its solid form. The ink is melted and dripped into a monolithic printhead where it is stored in a reservoir. Once in the printhead, ink flows through fluidic manifold channels and is jetted out of microscopic orifices through the use of piezoelectric transducer (PZT) technology. A specially designed electric pulse is applied to the PZT that deflects in such a manner to produce a precise and repeatable drop volume. The drop is ejected in the liquid state and travels a small distance between the head and the transfer drum. The transfer drum is held at a specified temperature that is lower than the melting temperature of the ink. The ink drop deposits onto the drum and at some later time will approach the drum temperature due to heat transfer into the drum and into the ambient air. This drum temperature will keep the ink in a ductile viscoelastic state. When the image is complete it is transferred to a preheated media by passing between a high durometer synthetic pressure roller and the transfer drum. A high pressure is developed in the nip that compresses the paper and ink layer, spreading the ink drops and fusing the ink drops into the media.[2,3]

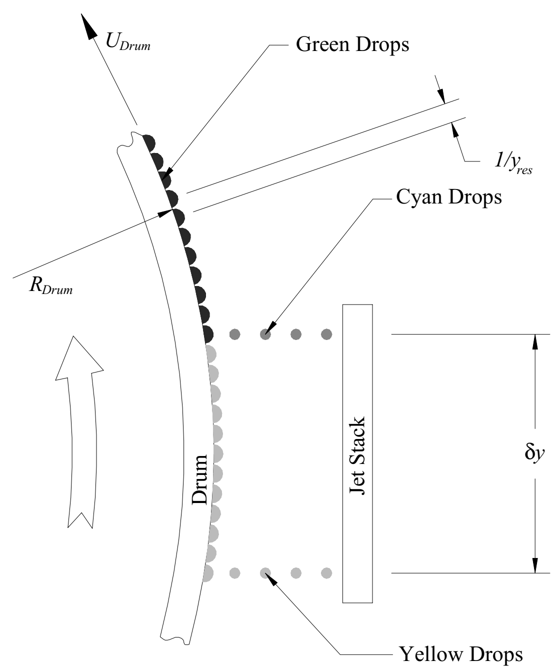


Figure 1. General architecture of a phase change printer

The Phaser 8400® is a CMYK color printer in which secondary colors, RGB, are created using combinations of two CMY colors printed ideally on top of each other. Figure 1 demonstrates a solid ink printer making a single pixel wide line of green. The drum is spinning in a counter clockwise direction while a printhead is depositing drops on the drum. Yellow drops are first deposited onto the drum. The drum continues to travel in a counterclockwise direction until a stream of cyan drops is also deposited on top of the yellow drops, thus making green drops. How well the two drops that make up a secondary color are aligned in the x direction is critical to secondary solid fill lightness and hue. If neighboring pairs of jets are misaligned by different amounts they will create a streaking print artifact. It is critical for secondary solid fill image quality that the variation in x direction color-to-color dot position be as small as possible.

Dot Position Amplification

Color-to-color dot position is typically measured by making single pixel wide lines of each color, printed as primaries, on a piece of paper and scanning at some adequate resolution. The centroid of each single pixel line is calculated by processing the resulting image. Figure 2 is a micrograph of a cyan line and a yellow line, both single pixels wide, butted against each other. It is intended for the centroid of these lines to have the same x-position. Due to manufacturing tolerances there is always slight color-to-color variation, which is referred to as δxp, i.e. the x position errors of the 2 primary colors relative to each other.

It has previously been assumed that the x direction dot position error of two lines is the same when printed as primaries or printed together as secondaries. Figure 3 is a micrograph of a stream of cyan drops being put down on top of a stream of yellow drops. Similar to Figure 2, there is an initial misregistration of the two lines as can be seen from the bottom of Figure 3. However, as the cyan ink begins to land on top of the yellow ink, the initial error is amplified. The color-to-color error as measured as a secondary is defined as δxs, which from Figure 3 is larger than δxp.

A method to measure color-to-color dot position of secondary lines has been developed at the Xerox Office Group. Although the details the method is not presented here, the results of the measurement are. Figure 4 is a plot of color-to-color dot position of individual lines as measured as primary lines versus when they make up secondary lines. The values in Figure 4 have been normalized by the diameter of a deposited drop. If there were no amplification of dot position errors the plot should have a slope of unity. The slope of the center section of Figure 4 is referred to as the amplification factor, γ. Figure 4 clearly shows γ to be much larger than unity.

The data points in Figure 4 make an ‘S’ shape. The slope of the center of the scatter has a high amplification factor. However at the edges of the slope, that is when the initial primary dot position error was high enough, the slope returned to something closer to 1.0. The hypothesis of this slope reduction is due to the drops being so far off that the top drop no longer lands on the bottom drop and thus is acting like a primary drop. This is consistent with measurements of ink drop sizes before the image is transfixed.

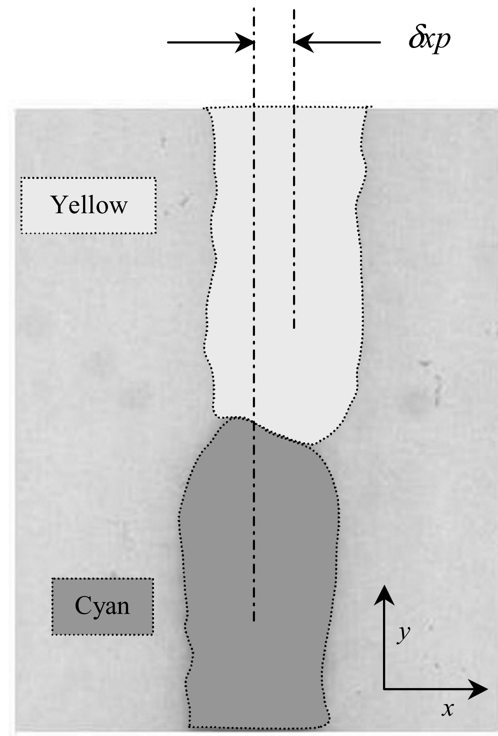


Figure 2. Typical x-direction color to color dot position error of two lines that are not coincident. Note image has been enhanced for clarity

It is believed that the first drop freezing before the second drop lands on top of it causes the amplification. If the second color lands slightly to one side it appears to ‘fall off’ and increase the dot position error. The physics of this ‘falling off’ is not understood. Currently Ashgriz et. al. are developing models that will allow us to understand this phenomenon better [4]. To investigate this hypothesis it is necessary to define an expression for the time delay between drop depositions.

Referring to Figure 1, assume the printhead is depositing drops at a frequency f_{jet} and the resolution of the image in the y direction is y_{res}, then the surface of the drum is travelling at

$$U_{Drum} = \frac{f_{jet}}{y_{res}}$$

The y direction distance from the cyan jet to the yellow jet is given by δy. Assume that the flight time difference between the yellow and cyan drop is negligible and make the small angle approximation. The time from when the yellow drop impacts the drum to when the cyan drop lands on top is

$$t = \frac{2R_{Drum}}{U_{Drum}} \sin^{-1}\left(\frac{\delta y}{2R_{Drum}}\right) \approx \frac{\delta y}{U_{Drum}}$$

Substitute in the expression for U_{Drum} and the delay time is approximated by

$$t = \frac{\delta y \; y_{res}}{f_{jet}}$$

This expression demonstrates that higher resolutions and greater physical y direction distance between orifices will increase the delay time while higher jetting frequencies will decrease the delay time.

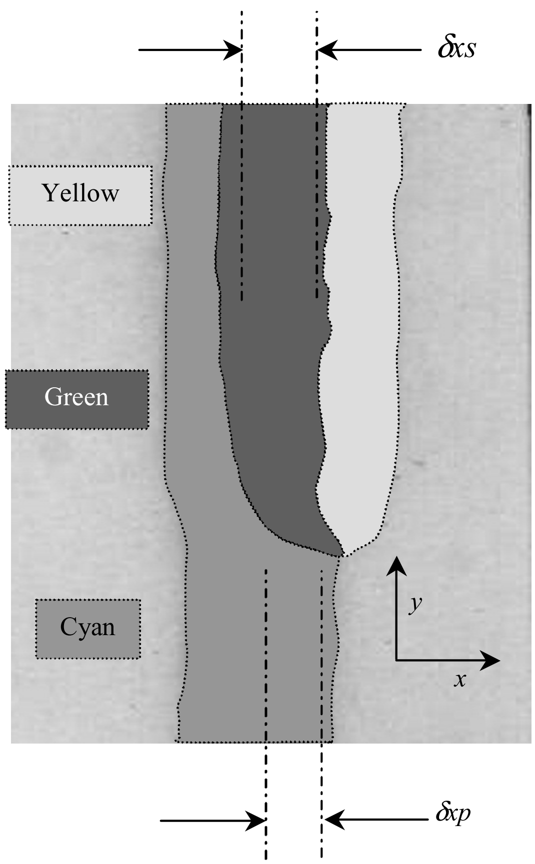


Figure 3. X-Direction color-color error amplification as line transitions from primary to secondary. Note image has been enhanced for clarity.

The theory that ink solidification was the cause of dot position amplification was verified by running a printhead at various jetting frequencies to alter the time delay between drop depositions, see Figure 5. The amplification factor γ approaches unity when the frequency is increased and the time delay is decreased. The amplification factor increases monotonically with delay time. If drop solidification is the cause of amplification, then Figure 5 implies that significant drop solidification must occur between 1 and 5 msec.

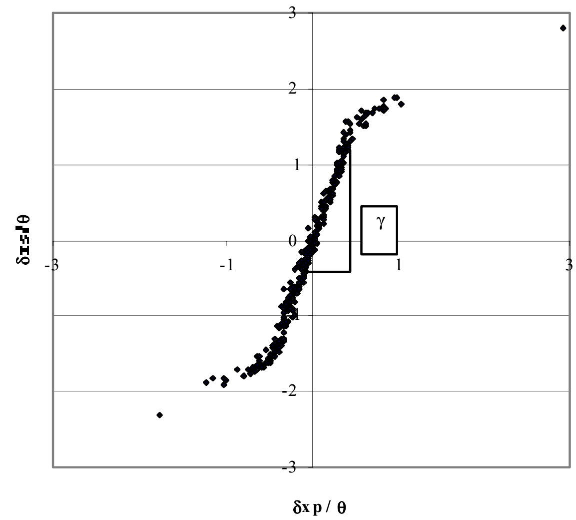


Figure 4. Correlation of primary color-to-color dot position to secondary color-to-color dot position.

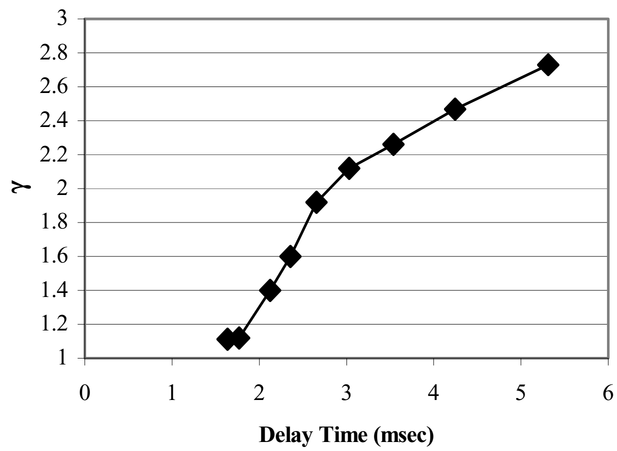


Figure 5. Amplification factor as a function of delay time.

For drop solidification to be the primary cause of dot position amplification, it is necessary for the drops to freeze in the time scales bounded by the previous experiments. As the properties and associated temperatures of the system are already known, a first order model was developed with ANSYS® to test the hypothesis. It has been shown by Snyder et. al.[1] that deposited ink drops on the transfer drum create a half hemisphere shape. The model is a half hemisphere drop that is initially at a uniform temperature, which is slightly less than the jetting temperature due to energy loss during flight time. The heat transfer during flight time was modeled with Flow3D®. The ANSYS® model included the heat capacity of the ink as a function of temperature so the solidification is modeled. Previous work by Bhola indicates contact resistance is negligible relative to internal drop conduction.[5] The outside of the drop experiences a convective film coefficient for a vertical heated plate. Figure

6 is the temperature of a solitary Phaser 8400® drop that has been deposited onto an aluminum substrate at the drum temperature. The lines are the temperature of the top of the drop, the center of the drop and the bottom of the drop near the drum surface. The temperature has been made dimensionless by dividing by the jetting temperature. The bottom of the drop quickly freezes and the rest of the drop continues to cool down. The ink of the Phaser 8400® freezes over a broad range of temperatures. The beginning and ending of the transition are also shown in Figure 6. Figure 6 clearly shows that at about 1 msec most of the drop is still molten. At about 5 msec the entire drop is completely frozen or in transition. These time scales match the previous analysis of where drop position error amplification occurs.

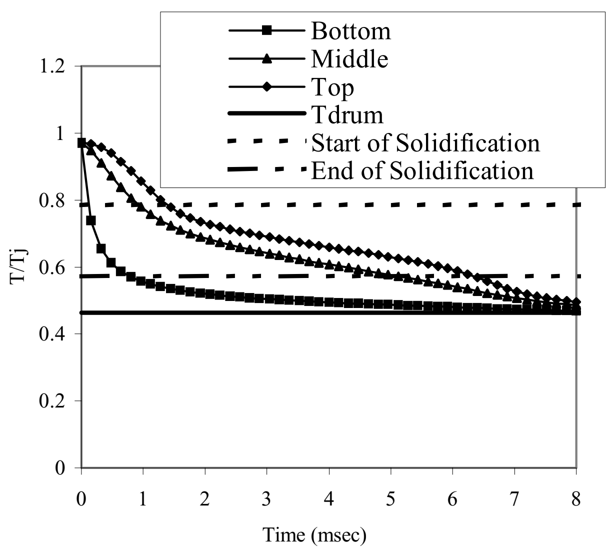


Figure 6. ANSYS model of drop solidification as function of drop mass.

Mitigation

Given that the cause of amplification is due to drop solidification there are four methods to improve secondary dot position. The first is to keep the drop molten longer. This can be managed by increasing the drum temperature in the printer, the mass of the drop or the jetting temperature, all of which are not feasible. The second method is to decrease the delay time by either increasing jetting frequency or decreasing the y direction distance between drops, which is also not practical. The third method would be to increase the dot position accuracy of the primary dot placement and accept the amplified secondary dot position errors. The primary dot position precision is limited by the capability of the orifice manufacturing process and difficult to improve. The Xerox Office Group instead looked at intentionally misregistering the orifice colors relative to each other. This was done to take advantage of the lower slope edges of the 'S' curve shown in Figure 4. By intentionally misregistering the orifices relative to each other it is possible to significantly reduce the variation in secondary dot position errors as shown in Figure 7, again Figure 7 is normalized by the diameter of a deposited drop. Even though the first drop is frozen, the second drop lands to the side and is not amplified. The maximum improvement occurs when colors are misregistered by ½ of a pixel in the x direction because any more misregistration will cause the top drop to impact the bottom drop on the next column. There are many ways to offset the colors, but Figure 8 shows the implementation of offset orifices for the Phaser 8400®. This configuration was chosen so red and green would have the optimal misregistration. The orifices for cyan and magenta are close enough together in the y direction that the amplification is acceptable.

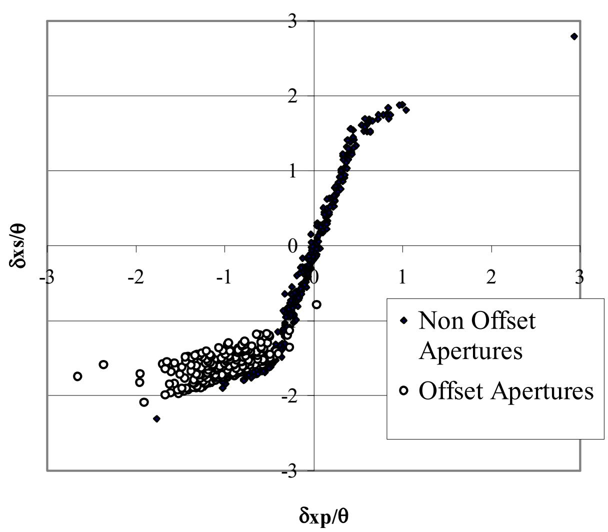
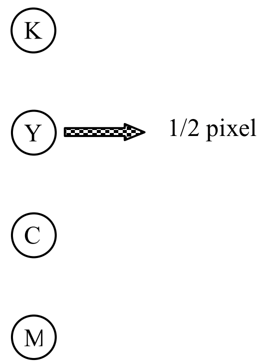


Figure 7. Drop mass amplification of offset and non-offset apertures in the Phaser 8400®.

A solid fill image quality measurement system has been developed at the Xerox Office Group as a metric to test improvements expected from intentional misregistration of images. It measures ΔL* deviations for various spatial frequencies. Smaller values indicate more uniform image quality. Figure 9 demonstrates the results of secondary image quality before and after the orifice misregistration shown in Figure 8. As predicted the misregistration significantly improved image quality red and green and had a negligible impact on blue.

It seems counter intuitive to intentionally misregister two primary colors to increase image quality. To ensure that other aspects of image quality was not sacrificed to improve solid fill uniformity a colorimetric study was done. The results showed that the color uniformity was indeed improved but there was a small loss in lightness and hue but was a reasonable trade off for the improved secondary image quality. Single pixel secondary lines were also studied and even though the two primary colors were not registered on top of each other at the microscopic level they appear as a secondary color at the macroscopic level.



Red - Offset by ½ pixel
Green - Offset by ½ pixel
Blue - Offset by 0 pixel

Figure 8. Orifice Offsets for the Phaser 8400.

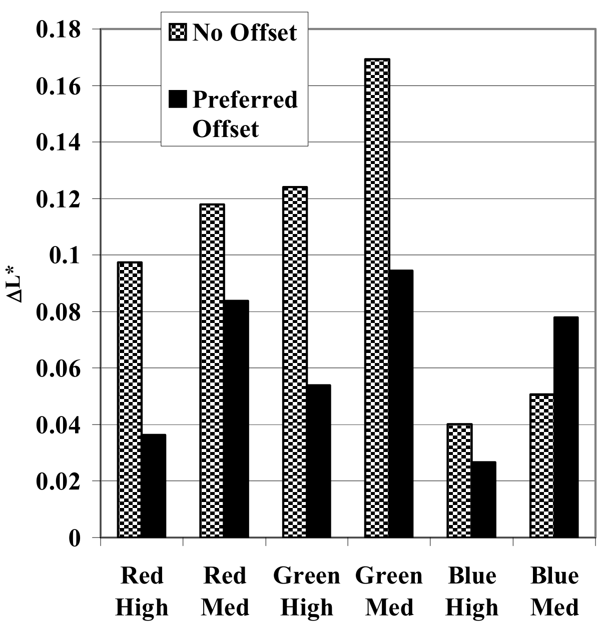


Figure 9. IQ improvement with Phaser 8400® offset.

Conclusion

Dot position amplification is a problem with phase change inks being used in an offset printing architecture. The amplification is caused by drop solidification of the first drop in a secondary pair. Adjusting the delay time between secondary drop pairs and affecting the amplification factor confirm this hypothesis. Also a first order FEM analysis demonstrated the drop solidification time scales are consistent with the delay time variation experiments. This problem gets more significant as drop mass get smaller and printing resolutions get higher without a comparable increase in jetting velocity. Reducing delay time between secondary pairs or increasing the solidification time are not practical solutions to this issue. It has been found that this problem can be mitigated by intentionally misregistering one color versus another by some fraction of a pixel. The maximum improvement is achieved if the two colors are misregistered by ½ of a pixel. The solid fill uniformity is significantly improved and the loss of lightness and hue is acceptable. Single pixel secondary lines appear fine at a macroscopic level.

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Biography

Jim Padgett received his B.S. degree in Mechanical Engineering from the University of Colorado at Boulder in 1986 and a M.S. in Mechanical Engineering from Portland State University in 1992. Jim is a principle engineer and has worked on printhead and inkjet development for the Xerox Office group in Wilsonville Oregon for 11 years. Jim is a registered professional engineer with the state of Oregon.