Establishing Inkjet Printhead Jetting Performance and Tolerances with Overall Printing System Design

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Abstract

Establishing the required specifications for a printhead is a balancing act between jetting performance, physical interfaces of the printhead and application requirements for building a quality printer. Selecting tolerances impacts printhead cost and system cost. This paper will review the tolerance and performance specification and metrics of the Dimatix Sapphire printhead, analyze drop placement errors as a function of these tolerances and examine how tolerances can be balanced to take advantage of the capability of some of the tolerances. Some tolerances can be balanced within the assembly; others can be used to improve overall performance of the printer itself, or to open tolerance requirements on the printer.

An example of this is the straightness capability in the cross process direction. The maximum standard deviation of straightness for the Sapphire is 3.5 milliradians. This is the highest value allowed for any given printhead. Overall, however, the distribution of this parameter is very tight for the measured population. Using a Weibull distribution to describe the population, the majority of printheads have a standard deviation better the 2.0. Very good straightness can be balanced with the tolerances on the registration features of the printhead to the frame, which potentially reduces the cost of these features. Other options can be to increase the standoff of the head over the substrate to open up the possibilities for substrates, or to reduce the tolerances for the media handling.

Introduction

The product specification and tolerances of the Sapphire are evaluated using RMS and Monte-Carlo methods. The product specification for the Sapphire printhead describes the limits for the tolerances, for both the physical dimensions as well as jetting characteristics. Applying an RMS tolerance analysis with these tolerances to determine the requirements for a printer system indicate that very tight tolerances are going to be required for carriage standoff, substrate management as well as carriage yaw and other system components. These requirements will add cost to the printer. Evaluating these tolerances, however, using a statistical approach and the capability data for each metric indicates very good fit for use.

To complete the analysis, several assumptions are made. It is assumed that a UV ink on a glossy paper is being used. The relationship between the ink, the paper and the printhead affect spot size and the variation of spot size in relation to drop mass and cross talk variation. It is also assumed that a 30 ng drop is used to achieve acceptable imaging in a 600 X 600 resolution. The resulting pixel size is 1.67 thousandths of an inch or 42.3 µm. At this drop size, a spot is expected to spread to roughly 106 µm in diameter on glossy paper (for this model). With perfect drop placement (no error in process or cross-process drop placement) a typical drop would cover the four corners of each pixel by approximately 20 µm. It is assumed that a stochastic image strategy is employed to reduce the impact of drop placement errors. This implies that any printhead in the system can address any pixel in the image and that neighboring pixels can be printed by the same nozzle or a difference nozzle on the same or other printhead. To evaluate the impact of velocity errors on Y printed spot position, a substrate speed of 1.25 m/s is used.

Tolerances Considered

Both physical and jetting tolerances for the Sapphire printhead are used. The mechanical tolerances of the printhead are pitch (the distance between jet 1 and jet 256), first jet to registration feature, parallelism of the nozzle row to the registration features on the printhead (referred to as “bezels” on the Sapphire), parallelism of the nozzle plate to the registration features on the bezel in the Z-axis, and Y-bow. For the system, printhead standoff is used.

The jetting tolerances considered are jet straightness in the process and cross-process directions, cross-talk and cross-talk variability within an assembly, velocity and velocity variability, and drop mass and drop mass variability. All performance metrics are evaluated at the same standard printing conditions defined in the product specification for which the jetting performance tolerances are given.

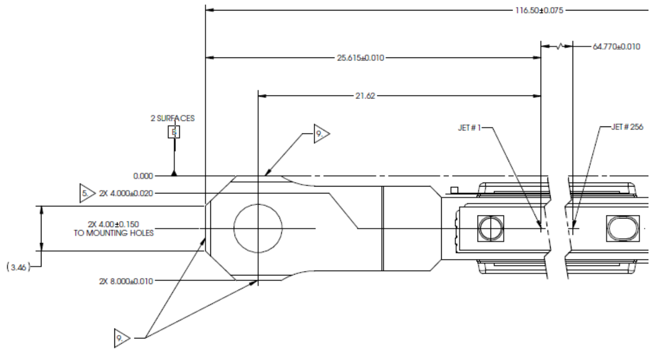

Figure 1. *Sapphire Interface control drawing with mechanical tolerances.*

Drop position errors in X and Y are nearly independent. The X direction will be the cross process direction or the direction along the row of nozzles, and Y will be the process direction or perpendicular to the row of nozzles.

Table 1. Sapphire product specifications for jetting performance.

	Sapphire		
Drop Size	Small	Medium	Large
Line Width, Maximum (%), ±	12	12	12
Line Width variability, one σ (%), max	3.3	3.3	3.3
Range Drop Velocity Mean (m/s), by PZT	7-10	5-8	5-8
Drop Velocity Variability, one σ (%), by PZT	.25	.25	.25
Velocity Crosstalk, Average, max (%)	-15	-15	-15
Jet Straightness, X-axis Error, maximum (mrad), ±	20	20	20
Jet Straightness, X-axis Variability, one σ, max (mrad)	3.5	3.5	3.5
Jet Straightness, Y-axis Error, maximum (mrad), ±	30	30	30
Jet Straightness, Y-axis Variability, one σ, max (mrad)	4.5	4.5	4.5

Errors in the cross process direction, X, are a function of the following mechanical tolerances: jet 1 location relative to the primary registration surface, nozzle pitch, and the variation in standoff, Z, from end to end. The jetting performance specification X - straightness is the primary tolerance in X ink drop location error. Both the worst straightness error allowed and the head average straightness are included in the printhead specification, for both X and Y straightness errors.

Jet 1 location error is the variation in the X location of jet 1 relative to the registration surface. Nozzle pitch is the distance between the first and last jets, and usually linear along the row of nozzles. The variation in standoff, Z, is the result of the error in planarity between the mounting bezels and the nozzle plate. Yaw has a negligible effect in this direction for individual printheads, where the jets are in a single row. X straightness error is indicated in milliradians and is the angle that a drop leaves the nozzle relative to the perpendicular trajectory.

Errors in the process direction, Y, are a function of the following mechanical tolerances: yaw and y-bow. The jetting performance specifications that effect drop placement errors are printhead average velocity, the variability of velocity from jet to jet, cross talk, drop mass offset and Y jet straightness.

Yaw is the error in the planarity of the two reference surfaces and the row of nozzles. Y-bow is defined as the distance of jet 128 position in Y, relative to the line drawn through jet 1 and 256. It affects only Y errors, as implied in the name. For the purposes of this discussion, Y-bow is assumed to be parabolic along the row of nozzles with the peak at the center. The printhead average velocity is the average velocity of the 256 jets. Velocity variability is the standard deviation of the velocity of all jets. Cross talk is a drop mass phenomenon that manifests in drop velocity. It is the amount the velocity of a single jet changes when its neighbors are turned on. Drop mass offset is the difference in the average drop mass of the odd jets and even jets divided by two. This is the result of having two sets of pumping chambers driven by individual PZTs, as in the case of Sapphire. This offset can be eliminated by using independent drive voltages for each PZT, but this is usually not necessary and rarely practiced. Y straightness is analogous to X straightness in Y.

Spot size is affected only by jetting performance variation. Drop mass variation affects the ability of a drop to cover the target pixel. The tolerances for drop mass variation are line width maximum error and line width variability, drop mass offset, and cross talk. The printhead average drop mass (PADM) variation is within the measurement tolerances of the calibration routine, ±1 ng. Sapphire printheads are calibrated to 30ng in the factory. The analysis showed that the variation in drop mass results in a very small change in ink drop size, however, the impact was kept in the Monte-Carlo model.

Line width maximum error and line width variability is measured using a printed image. Line width, as implied, is the width of a measured line and is indicated as a percentage where 100% is the width of the average line. Line width variability is the standard deviation of the line width of the 256 jets and is also indicated as a percentage. Drop mass offset is described above as well as cross talk. The variation in mass as a result of cross talk is derived from velocity cross talk data. A correlation between velocity and drop mass can be determined.

RMS Tolerance Analysis

Figure 1 shows some of the mechanical tolerances of the Sapphire printhead. These same tolerances are used for each of the printheads in the Sapphire product line. Table 1 has the jetting performance tolerances as indicated in the Product Specification. Using these tolerances, X, Y, and Spot size errors can be calculated using the root mean square method to determine pixel coverage.

X Spot Position Errors

From figure 1, the jet 1 position error is ±10 µm, and the pitch error is ±10 µm. The error in planarity between each mounting surface, which is the top edge of the bezel on each end, and the nozzle plate is ±80 µm. The total range is 160 µm. This deviation results in a 1.62 mrad error in jet straightness. This results in a 1.62 µm spot placement error at 1 mm standoff. From table 1, the maximum X-straightness error is ±20 mrad. The spot placement error to jet straightness is ±20 µm at 1mm standoff. The RMS error of these tolerances is ±25 µm at 1 mm standoff. At this error, the typical pixel is barely covered by the spot even with no error in Y.

Y Spot Position Errors

From figure 1, the error in planarity between the bezel reference features (2X) and the nozzle row is ±10 µm. This results in a total error for yaw of 20 µm. The y-bow error is specified at ±15 µm. The range of the printhead average velocity is 7 – 10 m/s. This gives an assumed average velocity of 8.5 m/s. A fast drop will have a drop placement error, at 1mm standoff with a carriage speed of 1.25 m/s, of 22 µm "ahead" of the average spot. A slow jet will have an error of 63 µm "behind" the average spot (-63 µm). Velocity variability within a printhead is 0.25 m/s. If ±3σ is used, a fast drop will travel at 9.25 m/s and result in a spot placement error of 11.9 µm. A slow drop traveling at 7.75 m/s will have an error of -14.2 µm. Cross-talk, at -15%, will result in an average drop slowing to 7.225 m/s with the resulting placement error of -26 µm. The condition of zero cross talk contributes no error. Drop mass offset is ±1.5 ng. This results in a change of .65 m/s to an average drop. The resulting error is -12.2 µm for a slow drop and 10.4 µm for a fast drop. Using an error in Y of half the yaw error (a jet at the middle the printhead), the RMS error in Y for a slow jet is – 79 µm, and for a fast jet is 44 µm. If the typical spot lands on average in the middle of these values (assumes a normal distribution) the error in Y is ±62 µm.

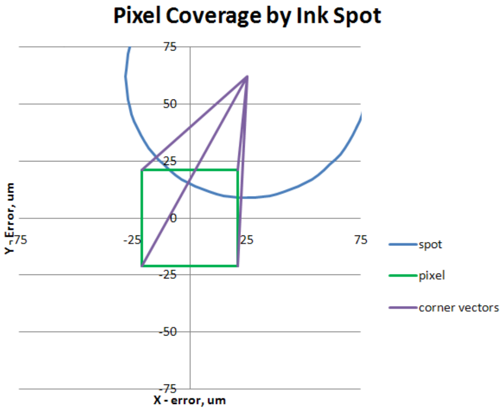

***Figure 2**. Ink spot, 106 µm in diameter, near a 600 X 600 dpi pixel.*

Figure 2 shows the relationship between the ink spot, the circle, and the target pixel using the RMS X and Y error information, and the ink spot size, at 106 µm. The lines from the center of the ink spot to the corners of the pixel are the corner vectors used to calculate the pixel coverage error.

Capability of the Sapphire

The capability of the Sapphire against the product specifications was measured as part of the product development process. Below are several plots of the distributions. The data was collected under laboratory conditions, using a model fluid. For the distributions shown, the Sapphire is quite capable against the product specification. The remaining capability data is contained within the analysis.

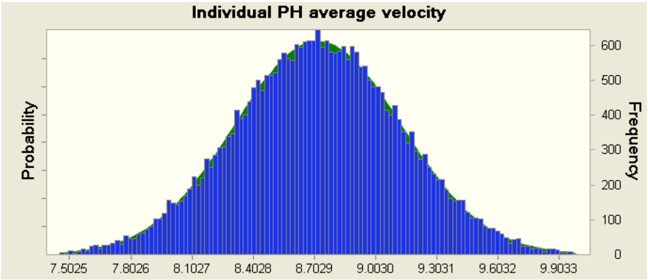

***Figure 3**. Distribution of head average drop velocity – normal distribution*

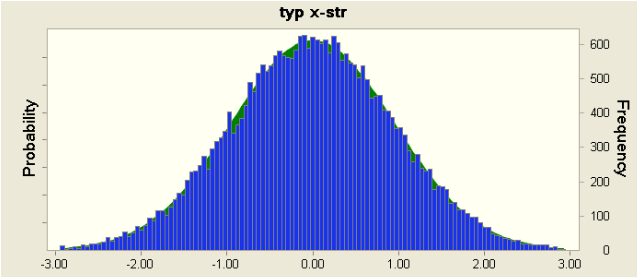

***Figure 4.** Typical jet X – straightness – normal distribution*

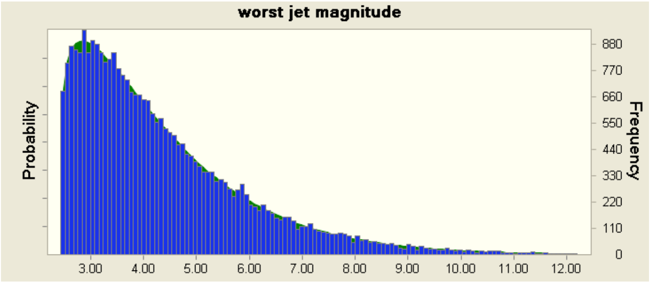

***Figure 5**. Worst jet X – straightness – Weibull distribution*

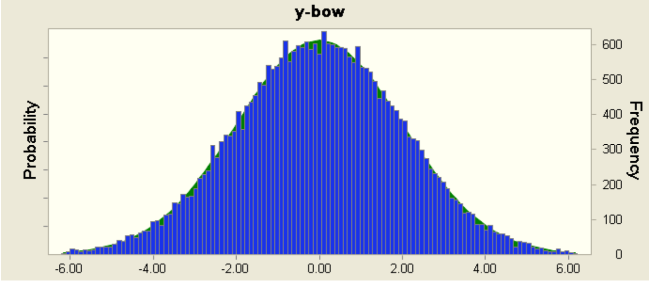

***Figure 6.** Y-bow distribution*

Monte-Carlo analysis

Using a statistical method for evaluating the capability of the Sapphire will take advantage of the fact that no single printhead is likely to exhibit characteristics at the limits of all specifications. Many of the distributions are normal, and centered at zero, such as X straightness error. The variability in X, the standard deviation of jet straightness within an individual head, is Weibull, and as a result, most printheads have a standard deviation of straightness toward the lower end of the specification.

Tolerance Analysis at 1 mm Printhead Standoff

The distribution for pixel coverage is shown below where the standoff is set to 1 mm. Pixel coverage is calculated as a measure of spot location relative to the target pixel corner, and is quantifiable. To calculate pixel coverage, the distance from the center of the ink spot to each corner is calculated. These four values are subtracted from the spot radius. If the number is negative, the corner of the pixel is not covered. The smallest or most negative value is selected from the four, and plotted. All pixels were covered at 1.0 mm standoff.

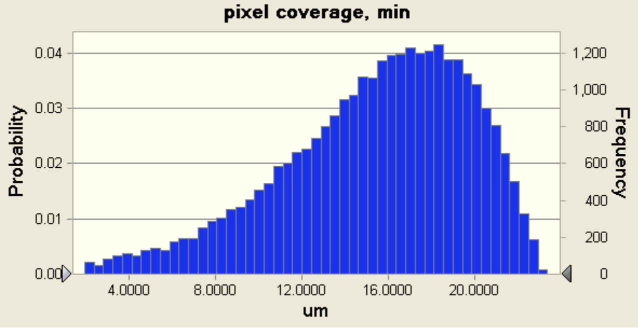

Figure 7. *Pixel coverage at 1.0 mm standoff*

Repeat of Tolerance Analysis with a 3 mm Standoff

The analysis of the printhead capability is repeated, but with a 3 mm standoff. As the height the printhead increases, straightness errors and velocity errors become more important. The impact of many mechanical tolerances tends to remain constant. The X position error distribution, figure 8, is the same in both the 1.0 m and 3.0 mm standoff cases. The Y position error, figure 9, has increased but the errors are still smaller than those calculated with the RMS analysis at a 1.0 mm standoff. Figure 10 shows the distribution of pixel coverage at the new standoff. Approximately 66% of all pixels are completely covered. In 94% percent of cases, at least 21 µm of the pixel is covered. An error of 42 µm results in a half covered pixel. If the system design is using a stochastic imaging strategy to minimize ink spot location error, then the pixels will likely be covered by neighboring drops from different nozzles limiting the amount of undesired white space.

Effects on Cost

Different printer manufacturers use different techniques for managing cost and the allocation of tolerances. Given the capability of the Sapphire printhead, more tolerance can be allocated to the printer than is indicated by the product specification.

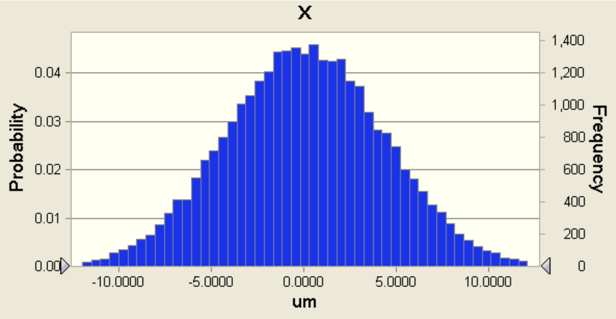

Figure 8. *X – Ink drop position error distribution at 3 mm standoff*

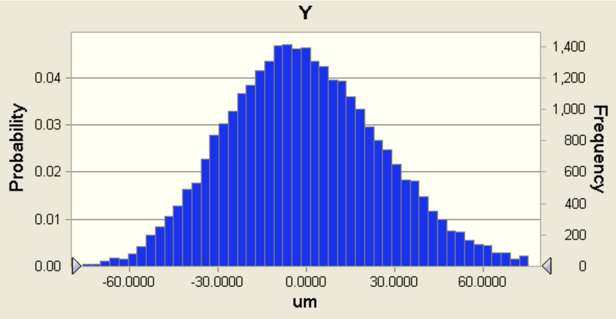

Figure 9. *Y-ink drop position error distribution at 3 mm standoff*

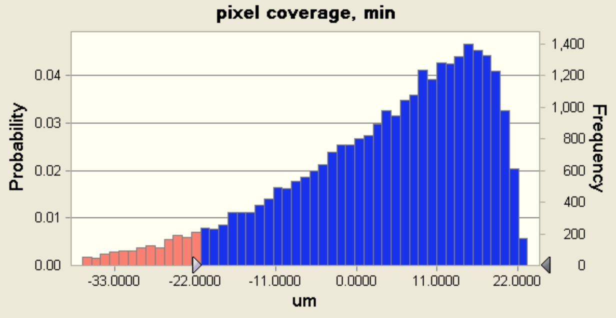

Figure 10. *Pixel coverage at 3.0 mm standoff.*

Biography

Thomas Duby received his BS in mechanical engineering from the University of Massachusetts (1989) and his MS in mechanical engineering from the University of Massachusetts (1992). Tom joined Dimatix in 1997. He has been involved in the development of printheads, starting with hot melt printheads. Tom was most recently involved in developing and releasing the Q-class product line.