System-Level Inkjet Performance and Reliability - Customer Needs and Innovations from Xerox

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Abstract

Inkjet systems are growing both in scale and in breadth of applications. This is particularly true with respect to production inkjet systems, digital fabrication, and industrial marking applications. There are systems now being designed and/or manufactured with up to hundreds of thousands of jets. To satisfy the requirements for throughput, image quality, materials compatibility, and reliability, printhead manufacturers are continuing to improve their design by offering more nozzles per inch, smaller drops, higher frequency, and other features. However, while the inherent printhead design may be the most important factor in achieving improved performance and reliability, there are many other factors that impact the system and are essential to achieving the desired customer needs in terms of quality, cost, and delivery. Sufficient understanding and design implementation of these system-level issues are as key to a successful product as is the raw printhead performance.

Introduction

Inkjet systems are growing both in scale and in breadth of applications. This is particularly true with respect to production inkjet systems, digital fabrication, and industrial marking applications. There are systems now being designed and/or manufactured with up to hundreds of thousands of jets [1]. Fig. 1 shows a sampling of the progression of the number of jets utilized in a printing system as a function of time for Tektronix/Xerox products.

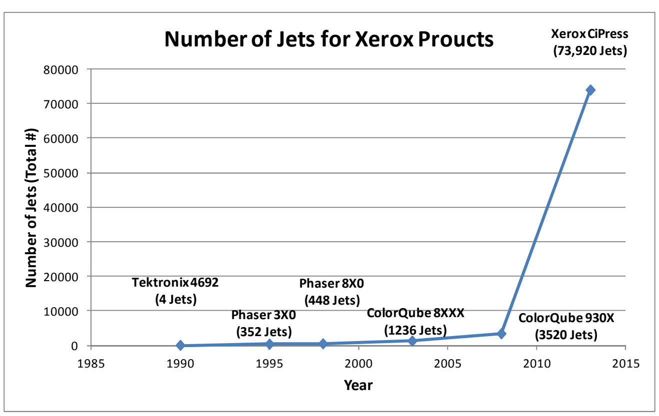

***Figure 1.** Xerox printing systems: total jets vs. time*

Fig. 2 shows the approximate number of jets in current high speed inkjet printing systems. To satisfy the requirements for throughput, image quality and reliability, manufacturers are continuing to improve their design by offering more nozzles per inch, smaller drops, and other features. The most fundamental of printhead specifications are the number

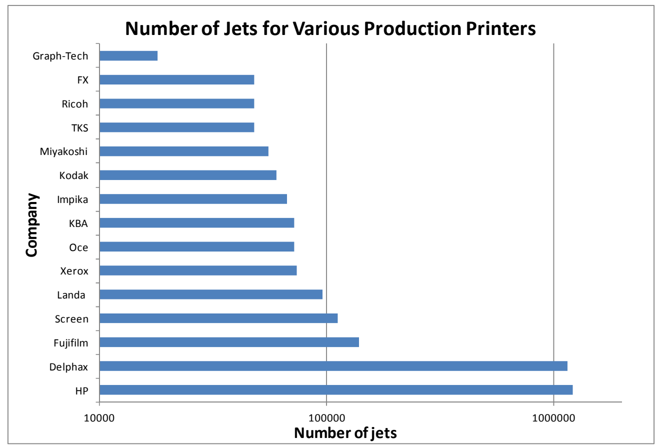

***Figure 2.** Total jets for various production printers*

of jets, drop mass, and jetting frequency. Accuracy of drop placement is an additional specification and refers to the ability to fire drops perpendicular to the printhead face is characterized by nozzle error distribution. Fig. 3 shows a typical plot of nozzle error distributions.

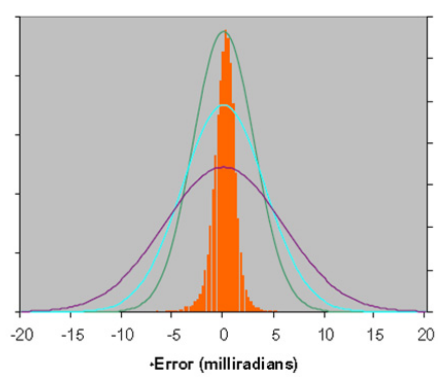

Figure 3. Nozzle error distribution

However, while these specifications are needed for good system design. there are many other factors that impact performance and reliability which are essential to achieving the desired customer needs. This data is nearly useless to the customer without a full understanding of the impact these quantities will have on wider system needs and performance.

Xerox industrial print head technology has advanced consistently over the past 25 years. Over this time, performance, print quality, and reliability have increased steadily while cost per nozzle has dropped dramatically. Continuous improvements have been made in materials, driver efficiency, packing density, flow rate, drop size uniformity, and manufacturing process capability [2]. This industrial head design includes the benefits of a multi-color architecture allowing mono, 2-color, 4-color and even 8-color operation within a single hardware implementation. Systems and methods are used which allow a reliable and long life high-temperature operation, the ability to jet over a wide viscosity range, extreme cost effectiveness, and extremely high volume flow rate. However, even with this said, other improvements and innovations important to the system requirements and performance have also been achieved. For example, print quality degradation can occur not only because of chronic missing jets and steady-state nozzle error distribution, but also due to intermittent missing jets, off-axis jetting, transient drop position errors, drop mass control and stability, alignment of multiple printheads, and adequate normalization control of velocity and/or drop mass of individual jets. Also, other important system topics include external contamination control such as abatement and thermal circuit design, external contamination mitigation including the purge and wiper system design, jet failure detection and single jet repair technology, jet redundancy, and missing jet hiding. Therefore, this paper is intended to briefly review the full set of customer needs and important system and subsystem capabilities and innovations required to achieve the performance and features for the next generation of highspeed inkjet systems, digital fabrication, and industrial marking applications. Sufficient understanding of the combined system-level issues are as key to a successful product as is the fundamental printhead performance specifications.

Printhead and Ink Design

The foundation of any inkjet system design is the printhead. There are many different printhead manufacturers and technologies. The most common technologies are typically characterized by the driver mechanism, i.e., piezo and bubblejet. However, in terms of industrial inkjet applications, bubblejet has severe limitations with respect to material compatibility, i.e., the fluid has to boil to be jettable. For this reason, many state-of-the-art industrial inkjet systems are built with piezo printhead technology. Also, new applications typically require new inks, and the ability of the printhead to accommodate different inks and materials is important.

The development of an inkjet system takes substantial time and money. Therefore, it is important to build a foundation with flexibility and robustness in mind. Xerox printhead technology is built by combining layers of stainless steel together at high temperature. The printheads achieve the ability to jet multiple colors by constructing thin channel manifolds that direct ink to individual columns of nozzles. These manifolds are interlaced with manifolds of other colors, so the channels span the width of the printhead. The structure of the printhead is shown in Fig. 4. Finger manifolds (1) channel the ink to the nozzles. (2) and (3) show the distribution of the two interleaved colors on the top half of the printhead and the other two interleaved colors on the bottom half. (4) and (5) show the same manifolds from the aperature side. The main manifold (6) supplies the finer manifolds with ink. The actual print head jet geometry columns repeat the full length of the head, as indicated by the arrows. The specifics of the design are well documented [2]. In terms of flexibility, different applications may require multiple colors. Single color printhead designs are the norm.; however, there are some 2-color designs as well. Current Xerox technology allows for 1, 2, 4 and even 8 colors to be used within a single printhead. This manufacturing process creates a diffusion bonded jetstack capable of high temperature operation and high materials compatibility compared to silicon-based designs.

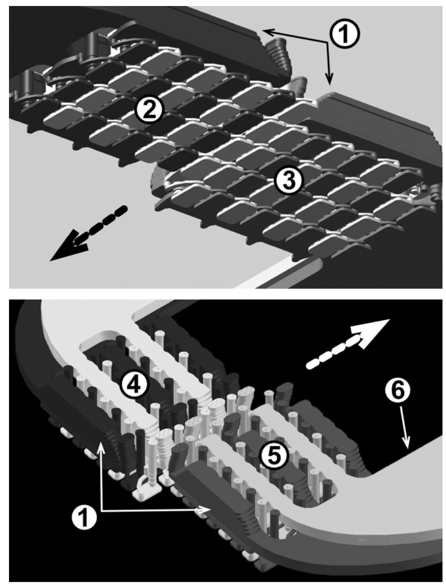

Figure 4. *1/2/4/8 color print head fluid path design*

Head life exceeding 5 years at 150C is commonplace with these designs. Also, remanufacture of the printheads is an additional benefit. The dropmass, number of jets, and jetting frequency together determine the flow rate of the printhead and the inherent resolution. Smaller drops are better for some applications (photo-quality documentation), while larger drops can be optimal for many industrial applications (ceramics, masking, textiles, 3D printing, and other industrial applications).

Printhead Normalization

Most inkjet applications can benefit from precise control of drop position, velocity, and/or intensity. Decreased drop misdirectionality leads to improved text and graphics, and/or more repeatable and more accurate industrial marking structures. As shown in Fig. 3, printhead manufacturers often advertise statistical misdirectionality based on individual jet performance. However, while this intrinsic printhead design controls some of the directionality, there are other system-level processes of importance, especially when considering the transient responses and the requirements of any specific application. This is especially true for demanding applications where multiple heads are stitched together and are used to print on dramatically non-uniform surfaces as that found on industrial and/or consumer applications with large and/or varying head to media gaps.

Printhead normalization involves techniques to manipulate the waveform and thus the drop size for individual heads and individual nozzles within a head. Fig. 5 illustrates a basic drive waveform for a Xerox industrial print head. These characteristic are documented [3,4,5].

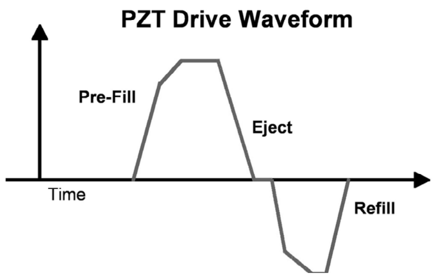

Figure 5. *Flexible waveform for printhead normalization*

For piezoelectric inkjet printing, the drop mass depends on the voltage profile applied to the piezoelectric element. The overall size of the waveform for any given printhead can be modulated to adjust the average mass. Also, a custom ASIC is used which allows segments of the waveform to be chopped at numerous levels of resolution below the peak-to-peak voltage and provides the ability to correct for jet-to-jet variations.

Fig. 6 shows a section of one possible test pattern used to measure the drop mass. The process direction is in the vertical direction. The test pattern is scanned or measured with an inline sensor or an auto document feeding scanner. The reflectance of a solid strip is used as a surrogate for the mass, and fiducial dashes are used to identify the position of each jet. The reflectance is measured and the jetting waveform is adjusted on an individual nozzle basis to achieve the best possible uniformity.

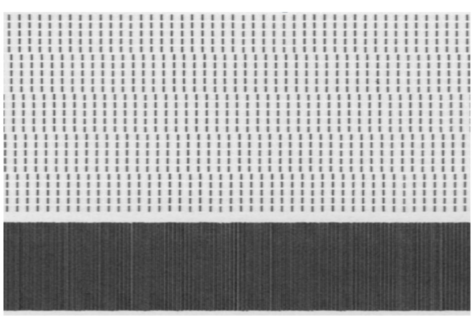

Figure 6. *Normalization test pattern*

Other errors can be corrected digitally with features built into the printhead which allow shifting of each pixel column, or each individual jet by an integer multiple of the resolution. Fig. 7 shows a cartoon of a horizontal line before and after this correction [6].

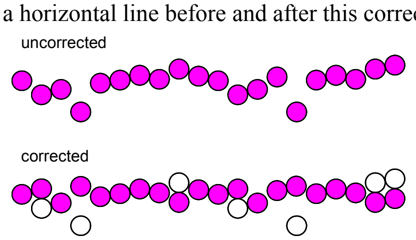

Figure 7. *Pixel alignment normalization*

In the figure, the process direction is in the vertical direction and it is seen for example that the fourth jet from the left is delayed. By shifting the pixel column of the individual jet that prints this digital image one pixel earlier, and making similar adjustment for some other jets, the horizontal line can be printed more accurately.

Other normalization methods are possible as well. For example, one can compensate drop mass changes that are intrinsic to the head or fluid. Specifically, jets fired at full frequency may have a different mass than drops fired in isolation as would occur in a low area coverage region. Individual waveform segments can modified on a head by head basis which offers another degree-of-freedom in product optimization. For example, Fig. 8 shows how this drop mass variation can be decreased for a multi-head printing system. Each graph plots drop mass versus firing frequency for full frequency and partial frequency [2].

While not required for every fluid, even though the drop masses can be equalized at full frequency, they may differ at the lower frequency. This results in head to head banding for light areas if uncorrected. The lower plot shows how the drop mass variation can be equalized among the heads, thus correcting or eliminating the banding.

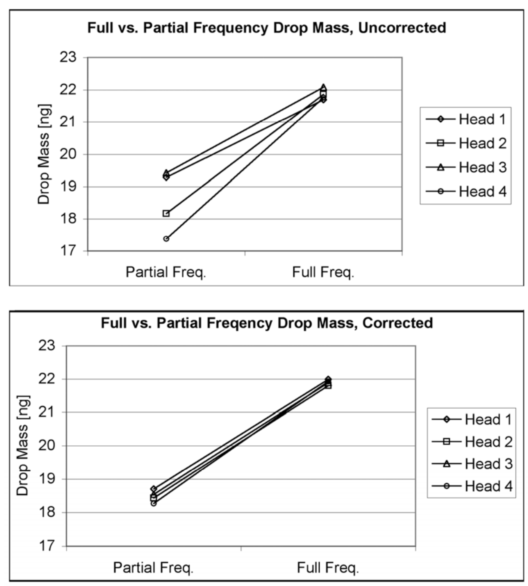

Figure 8. *Drop mass vs. frequency for both uncorrected and corrected multi-head printing systems.*

Transient Dot Position

The fundamental building blocks of any inkjet imaging system are structures consisting of full and half frequency lines and isolated drops [7]. Simple cartoon images and actual patterns taken from a halftone pattern are shown in Fig 9.

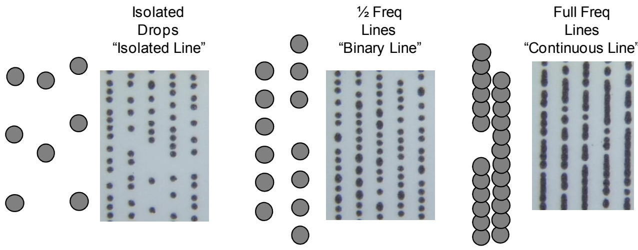

Figure 9. *Isolated pixels, ½ freq lines and full frequency lines*

Fig. 10 shows an example of these structures both normal (left) and with transient drop positional patterns and drop shape errors (right).

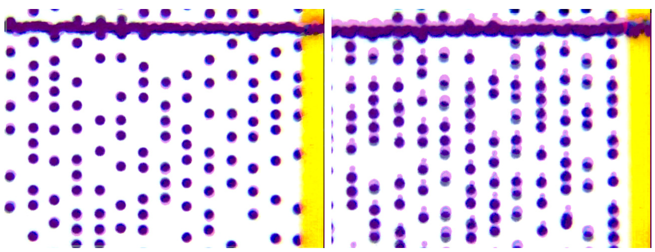

Figure 10. *Transient jetting example*

Such defects must be eliminated during the design phase and are particularly important parameters of study and characterization when implementing a new fluid. Hopefully, this example can help one appreciate the level of design and optimization required with respect to printhead performance and product requirements, etc... even above and beyond drop mass and normalization.

Multi-Printhead Layout

Economics, reliability, and manufacturability typically require that large inkjet systems be constructed with some form of a multiple printhead layout. For example, one possible arrangement of the print heads is shown in Fig. 11.

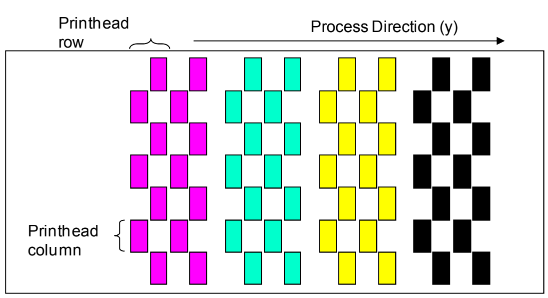

Figure 11. *Arrangement of prinheads for 4-color printing*

The print heads cannot be butted together, so the print heads must be interlaced to eliminate gaps when transitioning from one print head to the other. For example, in the Xerox CiPress, a print head row consists of 7 print heads and provides printing at a resolution of 300 spi in the cross process direction. A second pair of print box units can be interlaced with the first to increase the printing resolution to 600 spi. Some systems achieve this type of layout by installing multiple heads within a system, others create a module that incorporate multiple printheads. However, the size and of these systems is typically large regardless. The choice of architecture does not determine the performance. The performance is based on the technology and the engineering and includes things such as the achieved uniformity, the printhead life and cost (or cost per kiloprint, etc…), the ease of serviceability, and ease and/or automation of alignment, etc…

Registration

A misalignment between printheads exceeding about 20 microns will lead to an objectionable white space if there is a gap, or a dark line if there is an overlap. These tolerances can be difficult to achieve and maintain, because of manufacturing tolerance, measurement system accuracy, and thermal expansion. Therefore, to maintain good image quality, it can be advantageous to continually monitor and adjust the registration between the print heads across the print zone. In products both in the office and production, both the initial alignment of the print head array and the maintenance of alignment are automated with the use of custom closed-loop sensor systems. The Xerox ColorQube office copier uses an "Ink On Drum" (IOD) sensor and the Xerox production inkjet press CiPress uses a "Image on Web Array" (IOWA) sensor. These sensors operate by printing and capturing a test pattern that identifies the position of every jet and can thus infer the misregistration between printheads. If an analysis shows the print heads are not registered, an adjustment is performed. Each head may be potentially mis-registered in the cross process (x) direction, the process (y) direction, or rotated with respect to the process direction (roll). Fig. 12 shows an exaggerated cartoon of these registration errors between a subset of the heads.

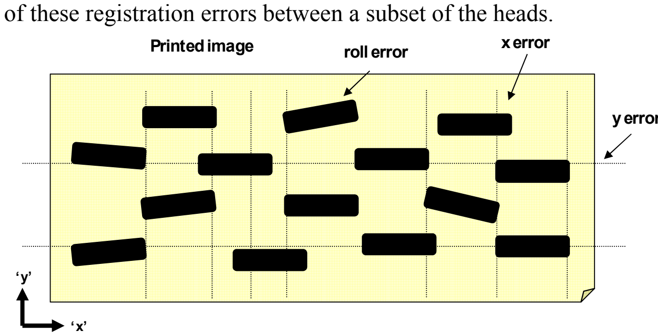

Figure 12. *Illustration of alignment errors between printheads*

Fig. 13 shows the actuators that can be adjusted to maintain registration.

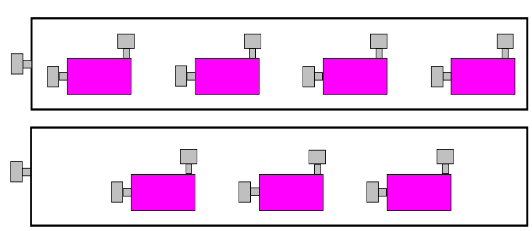

Figure 13. *Illustration of adjustment actuators*

Motors physically move the heads in the cross process direction and rotate the heads, while registration in the process direction can be adjusted by changing the delays in the firing of the jets. If the print head is not oriented perpendicular to the imaging path, the staggering of the nozzle array would lead to streaks due to an unequal spacing of the nozzles in the perpendicular direction. The unequal nozzle spacing can be detected from the registration or similar test patterns. A motor attached to each head can rotate the head relative to the web in order to recover an equal nozzle to nozzle spacing.

There are three types of cross process registration errors. If two heads of different colors are offset from their intended positions in the cross process direction, a color to color registration error occurs (x-series error). If two heads of the same color from different print box unit pairs are offset, then an interlace error will occur between the two 300 dpi heads (x-interlace error). If adjacent heads in a print box unit pair exists, then the nozzle spacing will not be equal as it transitions from one print head to another print head (x-stitch error). There is another set of motors that can be actuated in response to these registration errors. Each print head has a motor attached to it which can move the print head relative to other print heads. In addition, there is a motor attached to the print box unit which moves all the heads in the print box relative to the other heads. From an analysis of the registration test pattern, the entire set of x-series, x-interlace, and x-stitch errors between all heads are determined. From these errors, the displacement of each head from its goal position of zero registration error is determined. From the head position errors, a set of motor moves is found which will bring each head towards its goal position. The motors are all moved simultaneously. The registration is measured at regular intervals to ensure the heads remain in their goal positions. Process controls over these errors is particularly important in a continuous feed printer because the physical positioning of the web and hence the required proper head positioning varies with time.

Component and System Reliability

There are many layers and levels required to achieve high system level reliability. Focusing specifically on missing jets, one might consider splitting the requirements and efforts the following way:

1. Don't build in defects (during manufacturing)
2. Reduce external contamination (thermal circuit & abatement)
3. Mitigate the effects of any debris (purge & wipe system)
4. Automatically detect & repair problems (sense & recover)
5. Hide anything you can't fix (jet redundancy & hiding)

In terms of #5 above, jet redundancy and jet hiding is very important. For example, assuming that an individual component causes a failure (such as a missing jet), if a component is 90% reliable then putting 2 of them in series yields (0.90)*(0.90) or 81% system reliability. This is well known and can be generalized by equation (1)

$$R_{system} = (R_{component})^N \qquad (1)$$

Therefore, for a system with hundreds or thousands or hundreds of thousands of jets, in order to achieve even a marginal system level reliability, the individual component reliability (the reliability of the individual jets) basically must be close to unity. Of course, this is not practical. Equation (1) represents the case where the failure of a single jet is considered a system failure. However, if the jets are in parallel, i.e., they both have to fail for the system to go down, the basic math is much more forgiving.

$$R_{system} = 1 - (1 - R_{component})^N \qquad (2)$$

Equation (2) represents the case where jetting redundancy is being used. Failure occurs when any jet and the jet it depends on for mitigation of the failure have both failed. The same two part example but in parallel with 90% reliability yields 99% system reliability.

Abatement and Thermal Circuit Design

One way to minimize missing jets is to minimize the possibility of print head contamination. This can be achieved by controlling airflow away from the heads where contaminations may lodge. Thermal circuit design speaks to the requirement for the removal of waste heat produced by components to keep them within permissible operating temperature limits. Fig. 14 shows a schematic of an airflow design which optimized thermal and regulatory requirements as well as mitigated particle contaminates.

Such designs typically require up-front CFD analysis, mock-up and testing, as well as subsystem collaboration and design innovation. For example, Xerox office products have several innovative design features which isolate the printhead from contaminates. Once such design is the use of a labyrinth seal which allows sufficient mechanical tolerance for motion control, and yet restricts the flow of air and contaminates in the vicinity of the printhead. Another such design innovation which is implemented in the ColorQube 920X/939X products is a low-cost active abatement system which utilizes an impingement plenum/blower system to vacuum particles off the surface of the imaging drum. An example of such a system is shown in Fig. 15.

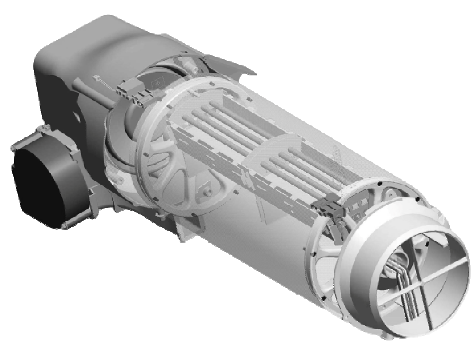

Figure 14. *Box thermal circuit design*

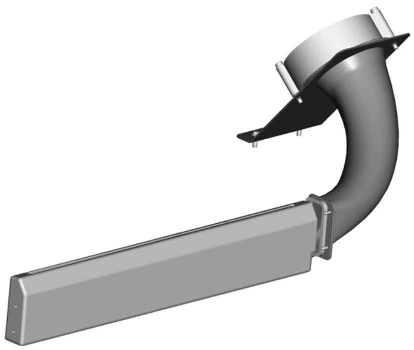

Figure 15. Particle abatement design

The CiPress production inkjet system uses a web cleaning system. These innovations are used to minimize jet contamination at the printhead and dramatically improve system reliability.

Purge and Wipe Systems

Proper design and implementation of the purge and wipe system is key to proper inkjet performance. The system is designed to be compatible with both the printhead (especially with respect to the anti wetting coating) and the ink. These systems must be designed and optimized together in order to maximize performance, life, and reliability. Without proper care, a printhead will not operate to specification. The basic requirement of the purge system is to flow ink through the nozzles in order to remove entrained air bubbles. However, if done correctly, this system can also be used to clean and refresh the surface of the printhead and mitigate the chance of particle contamination. For example, following the purge, a blade is mechanically moved across the jetting surface, removing the residual ink which could cause jetting failures. Numerous design innovations

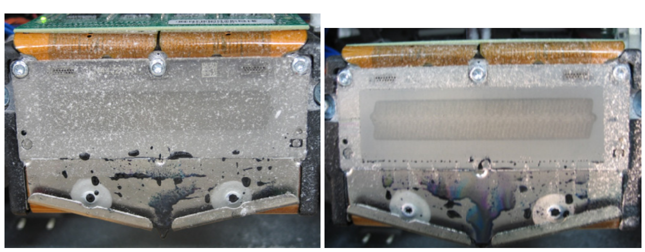

Figure 16. Before and after images of a printhead showing proper printhead maintenance

are used to optimize this system. Innovations in head maintenance can lead to a 500% increase in reliability related to intermittent and/or chronic missing jets under extreme contamination environments [8,9,10]. Fig. 16 shows before and after images of a jetstack from a purge optimization test. The details of such innovations include proper care during operation, non-operation, power-up and power-off. Proper design can achieve extremely high reliability (~ zero internal contamination errors) even for extreme conditions as that shown above. Even small errors in design can results in catastrophic failures.

Missing Jet Detection and Correction

Xerox utilizes different technologies to detect and correct for missing jets depending on the product requirements. For example, in a office printer, a simple missing jet test page is used and the missing jet is manually input into the device by the customer. A sample of this pattern is shown in Fig. 17.

Figure 17. Light stripes test for office printers

In an office copier, an Ink on Drum (IOD) sensor is used to detect missing jets. The sensor is a linear array similar to that found in scanners and is able to detect each individual color against the offset imaging drum surface. The printer has sophisticated software which tracks and hides missing jets and even recovers certain jets during non-work hours [11]. A sample of this pattern is shown in Fig. 18. Note the appearance of the missing jet near the center of the image.

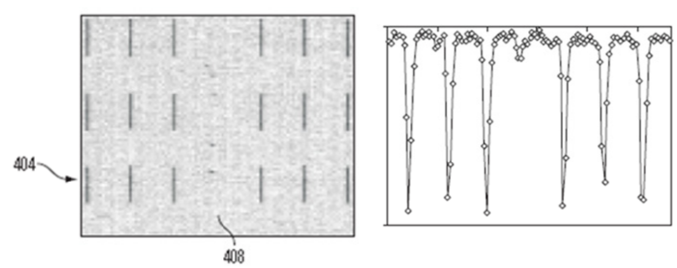

*Figure **18.** Light stripes test for office printers*

In the Cipress continuous feed printer, there are two options for monitoring missing jets on the printed page. For the first option, a test pattern similar to that shown in Fig. 18 is printed in place of a customer image. The test pattern is imaged with the IOWA sensor and eliminated from the customer image when the web is cut into pages. Under some circumstances, this approach is undesirable. An alternative is to print a sparse interdocument zone (sparse IDZ) image. In a sparse IDZ, a subset of the jets is printed on the cut line between the customer images. A different subset is used on each cutline so eventually all the jets will be monitored. As little a a single drop of ink is used per jet to minimize the visibility of the ink. Rather than aligning the drops from the set of jets in each sparse IDZ, they are slightly dispersed in the process direction to render the test pattern less visible (Fig. 19). The pattern is captured at regular intervals by the IOWA and then the page is cut exactly through the sparse IDZ. Because it lies at the edge of the print, the drops of ink are not visible except under magnification.

Figure 19 *– Sparse IDZ*

If a missing jet is detected, Xerox products use jet hiding technology which allows the drops that would be printed by the failed jet to be assigned to neighboring jets [12]. Figure 20a shows a 60% area coverage screen and 20b shows the white streak that would result from a missing jet. The 5 drops to be printed by the missing jet can be assigned to neighboring jets based on the available white space. The narrow white streak that would result from a missing jet becomes a white streak adjacent to two dark streaks as shown in Fig. 20c. The structure of this composite streak is at such a high frequency that it cannot be resolved by the eye and the resulting print appears uniform.

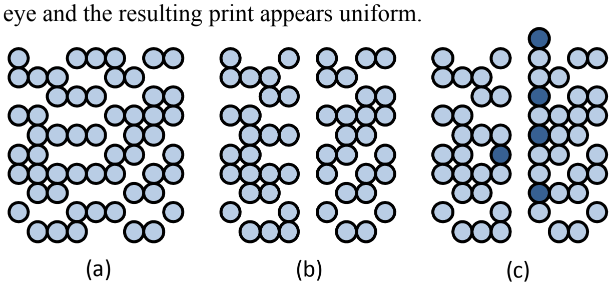

Figure 20 *– Replacement of missing jets by neighboring jets*

Missing Jet Recovery

Most internal particle failures are not permanent. However, a failed condition can remain for varying amounts of time depending on the usage and mitigations. Xerox utilizes different technologies to detect and recover missing jets. Some of the detection technology has been previously shown in the paper. Specific methods of recovery are proprietary and beyond the scope of this paper; however, it is worth mentioning for completeness.

Conclusion

Production inkjet, digital fabrication, and industrial marking applications are pushing inkjet systems into new frontiers of size and complexity, and these new systems are growing both in scale and in breadth of applications. There are systems now being designed and/or manufactured with up to hundreds of thousands of jets. Also, these applications require a broad range of new materials to satisfy market requirements. New printheads have been designed with higher frequency, more jets, and smaller drops. However, these heads are but the foundation of product design. There are many other factors which impact the system performance and reliability and are essential to achieving the desired customer needs in terms of quality, cost, and delivery. Sufficient understanding and design implementation of these system-level issues are as key to a successful product as is the primitive printhead performance metrics which are so heavily advertized. This paper outlines these capabilities with respect to the customer requirements. Some of the topics discussed include multi-color printhead capability, reliable and long life high-temperature operation, ability to jet over a wide viscosity range, extreme cost effectiveness, and extremely high volume flow rate. Other improvements and innovations important to the system requirements and performance are transient drop position errors, drop mass control and stability, alignment of multiple printheads, and adequate normalization control of velocity and/or drop mass of individual jets and/or multiple print head arrays. Other important system topics discussed include external contamination control such as abatement and thermal circuit design, external contamination mitigation including the purge and wiper system design, jet failure detection and single jet repair technology, jet redundancy, and jet hiding.

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