Drop-On-Demand Ink Jet Transducer Effectiveness

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Abstract

The effectiveness of drop-on-demand ink jet marking systems largely derives from the physical mechanism employed for creating the droplet ejection pressure. Electrostatic extraction of ink and various forms of piezoelectrically based mechanical contraction have been used commercially since the 1970's. The thermal ink jet (bubble jet) mechanism of liquid-to-vapor phase change expansion has become the dominant drop-on-demand approach just within the past ten years. Each of these physical mechanisms presents the full system with a different blend of strengths and weaknesses in areas such as ink property limitations, printhead design, manufacturing cost, thermal management, reliability, drop size control and electronics support. The trade-offs for high image quality applications are examined with particular emphasis on the inherent potential of shear mode piezoelectric printhead solutions versus thermal ink jet printhead designs.

Introduction

Images on paper or other inexpensive media and surfaces have long been a vital part of our culture. Images in soft display form, new in the past half century, are rapidly becoming accepted as alternatives to printed ones. Our electronic information systems with their soft displays are further changing the expectations we have for printers and printed images. A multipage document or color poster is a low cost, lightweight, compact, semi-permanent *display*. A printed page is an *output* of your information system, one you can pass on to others, sell, fold in your pocket, annotate, or post on a bulletin board. As an output of the system, or, especially, as *the* output or final product of the system, there is enormous need for these printed images to faithfully represent the quality (i.e. color, resolution) inherent in the electronic image. The "image printer" must provide this output at speeds and costs commensurate with the performance level of the system it serves. Ink jet technology and products are being developed by many companies in an attempt to fill this key need of modern information systems.

"Ink jet" is a phrase applying to many distinct technologies, most of which propel ink, imagewise, directly to the paper or medium under the control of a digital electronic image source.[1-3] The key feature is "directly to the paper". In other words, the physical process must manage to project the colored material mass from a supply point to a picture element (pixel) location. Electrophotographic printers use an intermediate, the photoreceptor, to first compose the marking material image and then transfer it, like a blanket, to the final medium. This approach is very successful for a monochromatic image but becomes rather costly for color images because the registration of multiple, unfixed, color separations is technically very difficult. An ink jet process can apply registered color separations directly to a simply- held receiver medium as long as the ink jet printheads are physically compact.

The very common wire dot matrix impact printing method is conceptually much like an ink jet process. An ink layer is transferred by pressure from a supply point (the ribbon) directly to the receiver in a pixel-by-pixel fashion managed by firing the wires at the correct times as paper and printhead are scanned past each other. The wire dot matrix impact process proved very reliable, and, even though noisy, won out over ink jet approaches of the 1970's and early 1980's. But wire size, motion, and durability could not be managed on a fine enough scale nor could printheads be made sufficiently compact for this technology to keep up with the rapid growth of the pixel content of electronic system images. Wire dot matrix processes are incapable of providing enough print quality bandwidth.

The promise of ink jet processes is their ability to retain the low cost, reliability, and color registration ease of a direct-to-receiver printing method such as wire dot matrix while providing the pixel density needed for today's images. Ink jet systems can produce spots as small as a few xerographic toner particles (10 microns) or a 2% dot in a 150 line halftone screen. Large arrays of jets can generate nearly 100 million pixels per second.

All ink jet systems benefit from the properties of liquids: surface tension and wettability, cohesiveness, and near incompressibility. These properties allow low cost,

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passive features in printhead structures (channels, nozzles, surfaces, pores) to control ink re-supply and pressure. Powder or "toner" jet analogs to ink jet are critically handicapped by the lack of these mechanisms in a powder. Surface tension forces are responsible for drop formation. Since the 1960's two rather different ink jet process uses of surface tension have been pursued: (1) continuous pressure and drop formation[1,2] and (2) intermittent drop formation, drop-on-demand (DOD)[3-6]. The continuous pressure systems control (synchronize) the natural break-up of a liquid jet by superimposing a significant pressure perturbation at one frequency within the band of natural break-up frequencies. While commercially successful in several applications[3] the complexity of the associated ink management and drop deflection printhead hardware has made these systems too costly for mainstream electronic information system printing.

The second technical pathway, drop-on-demand, uses a physical transducer to eject a single drop out of a nozzle by briefly overcoming the ink meniscus surface tension. Capillary pressure and surface tension are then allowed time to restore the meniscus before another drop is fired. There are many physical force mechanisms which can be imagined and most have been tried (i.e. electrostatic, magnetostatic, thermal expansion, mechanical impact). Two drop-on-demand mechanisms have weathered the test of time and commercialization: piezoelectric expansion and vapor bubble formation. For the balance of this paper the printing system strengths and weaknesses of these two ink jet processes will be examined. They are the leading candidate technologies upon which one might build the image printer our modern information systems need.

Piezoelectric Transducer Characteristics

The piezoelectric mechanism has been employed commercially in several geometries since the late 1960's. When an electric field is applied to a piezoelectric material or composite it changes it's dimensions a minute but useable amount.[3] Typically a cylindrical hollow shape elongates but narrows, a plate expands and thins, or, most recently, a plate shears like a deck of playing cards, expanding one of its diagonal thickness dimensions.[6] The piezoelectric material is configured as a clamped wall(s) of a liquid chamber so that the expansion of the material causes the wall(s) to push inward, squeezing the ink in the chamber. If the piezoelectric material is driven with a short rise time voltage pulse, the contraction of the chamber creates an acoustic pressure pulse having sufficient magnitude to overcome the ink meniscus in the nozzle, ejecting a drop. The amount of expan-sion of the piezoelectric material is very small, deriving from the slight shift of some atoms off their lattice positions when the electric field is applied. Many structure design factors are involved but the net result is that only (0.5 - 5.0) Angstroms of displacement, D_{wall}, can be achieved per applied volt in the (15 - 100) volt range.

Piezo Printhead Structure Efficiency, P_v

Because the amount of wall movement, D_{wall}, is so very small it becomes critical to manage the chamber volume displacement, $V_{displacement}$, needed to eject a drop of volume, V_{drop}. The piezoelectrically driven ink jet process depends on the propagation of an acoustic pressure wave to convey the contraction pressure to the nozzle meniscus. Any source of compliance in the printhead can absorb the acoustic pressure, defeating the dependable generation of a drop, especially the drop velocity. Velocities greater than 5 m/sec are highly desirable to achieve minimally acceptable drop firing straightness (good directionality) given the variability and strength of wetting forces at the nozzle exit edges. Common printhead fabrication practices which introduce sources of compliance include plastic components, thin walls, glue joints between layers in laminated as-semblies, sealing gaskets, the nozzle plate, and thin members introduced for acoustic damping. The ultimately stiff, acoustically efficient printhead would achieve a fast printing droplet with only one drop volume's worth of piezoelectric displacement. In practice printhead designers struggle to produce stiff printheads and often invoke geometries which harness acoustic reflections to add to the effect of the main contraction pulse. The ink jet efficiency of a structure can be characterised by a figure of merit, P_v the ratio of piezoelectric chamber volume displacement to drop volume (at a drop velocity greater than 5 m/sec). $P_v = 1$ is the ideal case structure. Practical results are in the $P_v = 2 - 10$ range. To summarize:

$$P_v = V_{displacement} \text{ (piezo chamber volume change)} \div V_{drop} \text{ (ink drop volume)} \quad (1)$$

$$P_v = \begin{array}{l} 1, \text{(Ideal)} \\ 2, \text{(State-of-the-Art)} \\ 4, \text{(Typical)}2 \end{array} \quad (2)$$

Printhead Transducer Packing Efficiency, P_A

Given the printhead structure efficiency above one can scope the transducer packing density problem posed by printing a given volume of ink. A conceptually useful approach is to calculate the areal packing efficiency, P_A the ratio of the area the piezoelectric chamber must occupy, $A_{chamber}$, divided by the area of the pixel, A_{pixel}, the ink jet marking system is required to produce. An ink jet pixel is a circular spot sized so that the circles touch on diagonals of the pixel raster, or resolution, R.

$$A_{pixel} = \pi / (2R^2). \quad (3)$$

For example, for R = 300 spots-per-inch (spi), the ideal pixel is a circle of diameter, $D_{pixel} = \sqrt{2}/300$ inches. In micrometers, the area of such a 300 spi pixel is $A_{pixel} = 1.13 \times 10^4\ \mu m^2$.

To estimate the piezoelectric chamber area, $A_{chamber}$, appropriate to generate the correctly sized drop for the system's resolution, R, two additional factors are needed: the drop spread factor, S_f, and the piezoelectric wall displacement, D_{wall}. The drop spread factor is the ratio of the pixel diameter, D_{pixel}, to the drop diameter, D_{drop}:

$$S_f = D_{pixel} / D_{drop}. \qquad (4)$$

The physical mechanisms which underlie the spread factor are complicated and poorly understood. Essentially this factor is a measure of the ink/receiver interactions, both chemical and physical, the ink physical properties, and the kinetic energy of the landing droplet. Environmental varibles such as temperature and humidity also play a role as they modify both ink and paper (receiver) properties. The ink is drawn by capillary action into the pores of the receiver's surface layer, either paper fibers or some other specially designed liquid receiver. Surface tension, ink/paper wettability, ink viscosity (hence temperature), receiver pore sizes and layer thicknesses, initial kinetic energy and evaporation rate all must be considered in the marking system design. Since quality printing on "plain" bond papers, those developed for xerographic copying processes, is the most difficult to achieve, system designers make the ink property and drop size choices to maximize performance on these receivers. The properties of the layers on special receivers, i.e. transparencies and coated papers and films, are adjusted to perform well with the "plain paper" ink choice. The highest quality printing on plain paper by drop-on-demand systems requires from 70 pL (picoLiters) to 150 pL per drop at 300 spi resolution. Lower quality, in terms of less optical density and more line edge raggedness, can be achieved with somewhat smaller drops by adjusting the ink properties to promote more spreading. Larger drops than 150 pL are disadvantageous because of increased problems with paper cockle and curl and ink bleeding between adjacent colors. At higher marking system resolutions, i.e. 400 spi or 600 spi, the optimun drop size is scaled back somewhat faster than linearily. A 70 pL drop has diameter $D_{drop} = 51\mu m$, and a 150 pL drop has $D_{drop} = 66\ \mu m$. The desired spot diameter on the paper for a 300 spi system is 120 µm. A slightly larger spot might be selected to account for drop placement noise or a slightly smaller spot to assist in controlling intracolor bleeding. So the typical spread factor range is:

$$S_f = 2.4 - 1.8 \text{ (for 300 spi, plain paper).} \qquad (5)$$

It was noted above that piezoelectric material movement is quite small, 0.5 - 5.0 Angstroms per applied volt. The higher values of movement are achieved by using very thin (i.e. 100 µm) walls so that the electric field is as high as possible at voltages accessible by low cost transistor drivers. The wall contractions are usually complicated shapes due to the configuration of the chambers.[4,6] For example the piezoelectric material wall might expand like a rectangular drum head into the chamber. To simplify this discussion it is assumed that the practical result of the constraints on piezoelectric material expansion, cost effective voltages, (10 to 100) volts, and chamber geometries is wall movements of (50 - 100) Angstroms:

$$D_{wall} = 50 \text{ Angstroms (Typical)} \qquad (6)$$

$$D_{wall} = 100 \text{ Angstroms (State of the Art)}$$

With the above relations and assumptions, the printhead transducer packing efficiency, P_A, can now be calculated:

$$P_A = A_{chamber} / A_{pixel.} \qquad (7)$$

$$P_A = (2/3)(\sqrt{2})\ (P_v) / ((D_{wall})(R)(S_f)^3). \qquad (8)$$

Using typical values for the factors in equation (8), the following printhead transducer packing efficiency is found:

$$P_A = 8000 \text{ (Typical Piezoelectric),} \qquad (9)$$

for R = 300 spi, D_{wall} = 50 Angstroms, P_v = 4, and S_f = 2.0. This means that in designing the typical piezoelectric printhead, ink chamber space must be found for 8000 times the area of the pixel the printhead is to write, for each jet in the printhead. It is this extraordinary packing density problem that impedes piezoelectric ink jet and which opened the door for the innovation of thermal ink jet.

Thermal Ink Jet Transducer Characteristics

Thermal ink jet (TIJ) printheads eject drops on demand also by very suddenly contracting an ink volume which communicates with a nozzle[8-10], causing the liquid pressure to overcome the ink meniscus. In this case the structure of the printhead remains stationary and some of the volume of ink is displaced by a vapor bubble caused by boiling a thin film of ink vehicle. The displacement generated by the liquid-to-vapor phase transition is tremendous. Pressures in the range of 70 atmospheres are generated at the moment of vapor phase nucleation. The vapor bubble pushes up from the heater surface to heights of 20 - 40 µm. Another helpful feature of the phase transition process is that once initiated the bubble "event" proceeds to completion without additional system intervention. This means that to eject a drop the system pulses the ink boiling resistor for a short time, 2 to 6 microseconds, and then doesn't have to return to that transducer until the next pixel position is reached, 120 to 300 microseconds later. This allows for significant cost savings through matrix addressing and the sharing of data and power lines to the printhead. Rather than the structural and packing considerations of the piezoelectric transducer, the major thermal ink jet transducer design problem is the materials challenge of constructing a resistor with excellent heat transfer into the ink layer while withstanding the tens of atmospheres of pressure when the vapor bubble collapses back to the liquid state.

TIJ Printhead Structure Efficiency, P_v

Thermal ink jet printheads, because of the excellent packing efficiency of the transducer described below, have the opportunity to be very compact and stiff locally in the region of the drop generator chamber and nozzle. For 300 spi printhead systems, the entire drop generator region from bulk ink resevoir to nozzle is only (200 - 400) µm. While glue layers and nozzle membranes may be used, their negative effects on the acoustic performance of the ink channel are minor on theis length scale. Indeed, thermal ink jet devices can operate successfully with air bubbles at the ink supply side of the 300 µm long ink channel, as long as the air bubbles are not so large as to cut off ink re-supply. A piezoelectric drop generator would be spoiled by the negative acoustic effects of such bubbles. The pressure impulse of a thermal ink jet bubble "explosion" does push liquid both out of the nozzle and backward into the ink supply region. Consequently the printhead structure efficiency, P_v, is in the range 1.5 to 2.5 for various configurations in commercial use:

$$P_v = 2.0 \text{ (Typical Thermal Ink Jet)} \tag{10}$$

TIJ Printhead Transducer Packing Efficiency, P_A

The vapor bubble which is formed over a pulsed resistor takes a half-pillow shape[9], driven by the huge volume change from the liquid to the vapor state. That is, it rises to a height on the scale of the narrowest dimension of the resistor. If the resistor is 40 µm wide then the bubble rises to nearly 40 µm. Effectively this is like having a wall displacement of 20 - 40 µm. For TIJ printheads, then, the analogous packing efficiency result to equation (9) above is:

$$P_A = 1.0 \text{ (Typical Thermal Ink Jet),} \tag{11}$$

for R = 300 spi, $P_v = 2.0$, $D_{wall} = 20\mu m$, and $S_f = 2.0$. The packing efficiency is better than 1.0 if a more energetic bubble is created, increasing D_{wall}, or for larger spread factors.

Thermal and Piezoelectric Ink Jet Compared

It is no accident that thermal ink jet technology has become commercially more successful than has piezoelectric drop on demand ink jet. The key advantage of TIJ shows in the transducer packing density factors, equations (8), (9), and (11):

$$P_A = (2/3)(\sqrt{2})\,(P_v) / ((D_{wall})(R)(S_f)^3), \tag{8}$$

$$P_A = 8000 \text{ (Typical Piezoelectric),} \tag{9}$$

$$P_A = 1.0 \text{ (Typical Thermal Ink Jet).} \tag{11}$$

This comparison shows that the TIJ printhead designer has 3 to 4 orders of magnitude spatial advantage over the piezoelectric printhead designer. Even if the piezoelectric structure is a state-of-the art shear mode configuration[6], the packing density factor only drops to 2000, three orders worse then the typical TIJ case. When only a few jets are needed in a system this advantage may not be overwhelming. For example piezoelectric systems with 100 jets have been introduced commercially and may be viable. However as speed, quality and color requirements push upward as noted in the introduction above, a thousand jets will be needed to provide a reasonably satisfying printer for the individual workstation. Tens of thousands of jets will be needed to challenge electrophotographic printers which serve many sharing users on large networks. When the system need for jets reaches these levels, there simply isn't space to economically pack and assemble that many piezoelectric transducers. The great packing efficiency of TIJ transducers gives this technical approach a real chance to configure the required thousands of jets.

Piezoelectric ink jet has one very significant advantage over thermal ink jet, ink formulation materials latitude. In thermal ink jet the ink itself, through the phase change mechanism, has to be constrained in it's design to reliably perform the liquid-to-vapor-to-liquid cycle. So far, only water has demonstrated adequate reliability and expansion performance to play this role. Thus it seems that TIJ inks will be aqueous for the foreseeable future. The piezoelectric mechansim has been used with a large variety of inks, including hot melt inks which are jetted in their liquid phase at elevated temperatures but quickly cool to a solid on the receiver. Piezoelectric ink jet printheads can, in principle, make use of any innovation in ink design which solves the intercolor bleed and drying energy problems of inks on plain paper.

Conclusion

Drop-on-demand ink jet offers the potential to yield the "perfect" printing method for our emerging, image intensive electronic information systems. However, two technical challenges have yet to be fully met: (1) Can a practical configuration of piezoelectrically driven chambers overcome the huge packing density problem inherent in the smallness of the piezoelectric effect? (2) Can an ink formulation innovation overcome the intercolor bleeding and energy intensive drying problems of the aqueous inks used for thermal ink jet? If innovators answer either challenge, ink jet will become the printing method of the twenty-first century.

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