Continuous Ink Jet Technology

John M. Schneider, Scitex Digital Printing, Inc.
Dayton, OH

Introduction

Continuous ink jet (CIJ) technology has emerged as an industrial work horse in a wide variety of applications from production serial number printing, to sophisticated "on-demand" printing applications. This paper will discuss the major CIJ technology types and their operation, along with some of the challenges which must be overcome for this technology to achieve its potential in the printing marketplace.

The central notion behind continuous ink jet is to create stream(s) of uniform drops which can be charged individually. Then, a downstream electric field can be used to separate print drops from drops to be discarded. The unused drops are typically called "catch drops." They are either discarded as waste, or recycled. The most unique aspect of the system is that *only the image touches the substrate.* This attribute enables the flexibility of CIJ systems which is responsible for much of the advantage of CIJ in the industrial marking industry.

Successful application of CIJ is dependent upon creation of a synchronous stream of uniformly spaced and sized droplets. A stream of drops has less surface area than a circular jet of fluid, so the effects of surface tension inherently disintegrate a jet into a series of drops. Naturally occurring jet breakup, such as is seen in a low speed stream from a faucet is driven by random effects, such as noise. It is a simple matter to make the disintegration, or breakup, of the stream highly regular by imposing *stimulation*, a mechanical vibration of the surface of the jet at its resonant frequency.[1-2] When the breakup is highly regular, the break-off point of the jet can be placed near an electrode, so that individual drops can be independently charged. Then, a downstream electric field can be used to sort different drops into different trajectories.

There are two commercially important CIJ types, classified by the drop selection methodology. Multi-deflection and continuous ink jet systems are illustrated in Figure 1. Both CIJ types embody the same technology elements, a drop generator, a charging system, a deflection system, a catcher system and an ink recirculation system. In the multi-deflection process, drops are charged and deflected to various charge levels. This enables a single jet to print a small image swath. In the binary process, drops are either charged and (typically) caught, or left uncharged and allowed to strike the substrate. In the binary process charging is simplified, but a single jet can only print a single pixel line. Imaging an area is accomplished with an array of jets, or by mechanically moving the jet relative to the substrate.

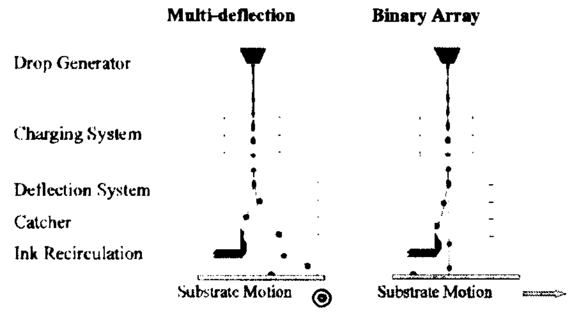

Figure 1. Types of continuous ink jet showing common technology components

Stimulation of a Jet

Jet formation is accomplished by forcing ink from an orifice under pressure. A properly formed jet is reminiscent of the smooth filament of water which will flow from a faucet when it is only slightly open. A significant difference is that practical jets for ink jet are about 1/3 the size of a human hair, and since the drops only exist for about one millisecond, gravity has a negligible effect on jet properties. Rayleigh[1] was the first to establish that a jet departs from cylindrical shape exponentially. In Rayleigh's analysis, the surface of the cylindrical jet is represented jet as,

$$r = a_0 + c \cos\frac{2\pi}{\lambda} z \quad (1)$$

Where λ is the wavelength of the disturbance on the jet, z is the distance along the jet, and c is proportional to $e^{\omega t}$. Rayleigh's analysis was to first to show that there is a "maximum instability rate" at a value of λ given by,

$$\lambda = 4.508 * 2a \quad (2)$$

where a is the radius of the jet. Incidentally, it was known prior to Rayleigh's analysis that jets are stable to perturbations whose wavelength is shorter than the circumference of the jet. CIJ people are very concerned with is the "lambda over *d*" of the jet. Typical CIJ systems operate near the maximum instability wavelength.

At the point in the instability process when a drop is about to disconnect from the jet, there is a fine ligament connecting the jet to the drop. Typically, both ends of the ligament disconnect to form what is called a "satellite" drop. Depending on conditions, the radius of the satellite can vary from a tiny fraction of the drop size to a size comparable to the "parent" drop. If the forward end of the ligament detaches from the drop prior to the end connected to the jet, the satellite has rearward momentum, and will merge with the next drop to be created, the “trailing” drop. Conversely, when part of the ligament attached to the jet separates first, the satellite formed has a forward momentum, and will merge with the “leading” drop.

If all else is equal, the determining factor in how a drop will merge is the stimulation *amplitude*. For a given λ/d, there is an interesting plot of satellite behavior. The pragmatic behavior is illustrated in Figure 2, which is a plot of break-off length vs λ/d[3].

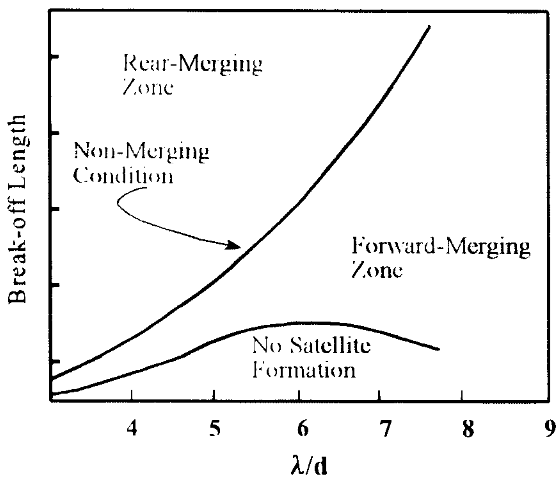

Figure 2. Satellite regimes vs. stimulation.

Synchronous drop formation can be obtained with very low stimulation amplitude (i.e. long break-off length.) At very low stimulation values, the satellites formed are “rear merging.” At higher stimulation amplitudes, satellites are “forward merging.” Curiously, there is a very sharp transition line at which the ligament connecting the drop to the jet snaps at both ends simultaneously, so the satellite has the identical velocity as the parent drop. In this case, the satellites do not merge. This is termed the “infinite satellite” condition. Operation in the this regime is problematical. The satellites tend to acquire a much higher charge to mass than the parent drops. The high charge to mass of the drops means that they are much more reactive to the applied electric field. Accordingly, they tend to crash into electrodes, and generally reek havoc with system reliability. The positive side of this behavior, is that the satellites are much smaller than the parent drops. This aspect was used commercially for a time in a multi-deflection CIJ system which printed with the infinite satellites. This enabled it to use a relatively large nozzle size for high resolution printing.

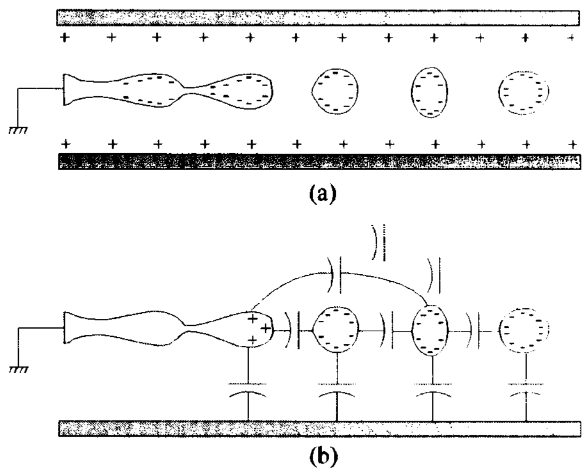

Figure 3. Charging geometry for a typical CIJ system.

Drop Charging

The CIJ printing process begins with charging the drops. At first glance, this is straightforward, but electrostatics is rarely as simple as it appears on the surface. The geometry of a typical charging system is shown in Figure 3. An electrode system surrounds the drop at the point of breakup from the jet. A positive charge on the electrode, induces a negative charge on the drops produced, as illustrated in Figure 3(a). When the voltage is changed to put a different charge on each succeeding drop, the situation becomes much more complicated. For example, suppose that after a succession of drops has been charged for catching, a single drop with no charge is desired. (This is exactly what happens in binary CIJ, where catch drops are charged and print drops are uncharged.) Simply reducing the charging voltage to zero, will not result in an uncharged drop. The presence of the leading set of charged drops, induces an opposite charge on the drop being formed. To get a desired level of charge on the drop being formed, account must be taken of the partial capacitance between the drop being formed, the charging electrode, and several leading drops. The *history* of preceding drop charges must be known, to determine the correct charging voltage for the drop currently being produced. The derivation[4] of the proper charging equation will not be reproduced here. The solution turns out to be of the form,

$$Q_n = -C_e\,(c_1 V_n + c_2 V_{n-1} + c_3 V_{n-2} + \quad) \qquad (3)$$

here C_e is a equivalent capacitance, and the c_i's are numeric parameters which depend on the physical geometry of the charging system. The number of terms which must be considered depends on the situation and the charging accuracy required. *Determining the proper charging voltage requires knowledge of the charging voltage of several prior drops.*

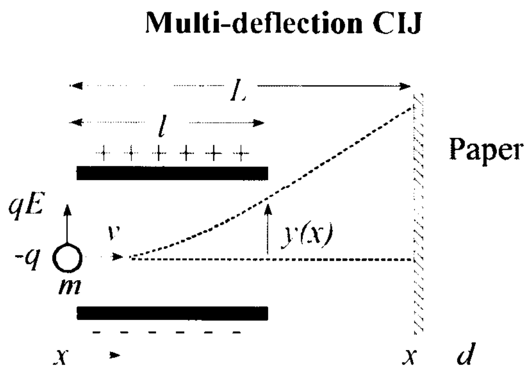

Figure 4. Representation of a deflection system.

Drop Deflection

The first order analysis of drop deflection is an interesting sophomore physics exercise. Providing an accurate model of drop deflection is a multi-year research project. A typical ink jet deflection system is shown in Figure 4. The following set of simplifying assumptions are made: The electric field created by the deflection plates is uniform, and is confined to the region between the plates. The effects of image charges is neglected. The effects of air on the trajectory of the drop is ignored. That is, the velocity of the drop in the direction parallel to the deflection plates, v, is constant. The drop has a mass, m, and a charge q. The electric field has a strength, E. With these simplifying assumptions," the analysis is quite simple. The result for the deflection, Y, is

$$Y = \frac{qEl}{2mv^2}(2L-l)$$

Multi-deflection CIJ

Aerodynamic and electrostatic interactions among drops determine the ability of a multi-deflection system to print with good quality. Eq. 4 provides a point of departure for analysis of drop placement errors in a practical system. For example, the velocity in Eq. 4 enters into the deflection quadratically. A one percent difference in velocity results in a two percent change in drop placement. This is significant, because aerodynamic effects tend to decelerate drops as they travel through the deflection zone. The result is more deflection than intended. A typical multi-deflection system may deflect drops twenty or more pixels, so a two percent deflection results in a nearly half pixel error! In a quality system, this is the entire error budget.

Because drops are strongly affected by the "wakes" of preceding drops, history effects are again introduced. The stream of drops moving towards the catcher creates a wake of moving air which surrounds the stream. If a single drop is deflected to a print zone, it moves from the catch stream wake, into relatively still air. In this case, it encounters significant drag, which slows it down. As a consequence, it is deflected more than it would be if it were moving behind another print drop. The drag forces become much more significant at higher resolution. The (Stokes Law) drag on a spherical drop at low Reynold's Number is proportional to it's radius, but it's mass varies with it's volume. Thus, aerodynamic effects become increasingly difficult in the development of a high resolution multi-deflection printer.

Electrostatic (Coulomb Force) interactions among drops are also influential in drop placement. In a high resolution system, the force between two charged drops separated by two lambda amounts to a few percent of the qE deflection force, but these forces act all the way to the print substrate. Accordingly, they have a strong influence on drop placement. The force, required to deflect a drop depends on the throw distance of the system. If the throw distance is long, aerodynamic forces will result in poor drop placement. If the throw distance is short, higher drop charge is required to achieve the required deflection, so the Coulombic interaction forces are higher. *Thus, there is an optimum throw distance* in a multi-deflection CIJ system, in which the best trade-off between aerodynamic and Coulombic forces leads to optimum drop placement accuracy.

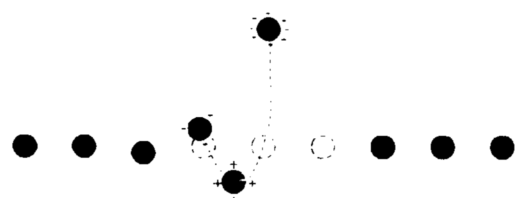

Figure 5. Effects of a single drop voltage pulse.

The simplest form of aerodynamic and electrostatic interactions among drops is illustrated in Figure 5, which illustrates a stream of drops moving to the right. At some point, a charging pulse is applied to a single drop in an uncharged stream. The dotted drops in Figure 5 show the where the drops would be positioned in the absence of the charging pulse. The drop charged by the positive voltage pulse on the charging electrode is deflected away from the drop stream. As it is deflected, it is slowed by the relatively still air away from the stream. Electrostatic induction effects introduce a positive charge on the first trailing drop, deflecting it downward. The second trailing drop receives a negative charge, predominately by proximity to the first trailing drop. In theory, the third and all subsequent trailing drops receive alternating charges. In practice, the magnitudes of these charges is to small to be of consequence. The dotted line connecting the deflected drops is shown to illustrate why the charging history effects are often called "*the j effect*".

When two or more drops are deflected, the combination of aerodynamic and electrostatic effects introduce "singularities" into the system. Figure 6. illustrates what is known as a "merge curve." The top of the figure shows two drops being charged and deflected from the drop stream. As in a practical system, a "catch drop" separates the two deflected "print" drops. The first deflected drop moves into relatively still air, and is slowed as a result. The second drop is deflected into the wake of the first drop, and is not slowed as much. As a result, the drops impact and merge at the point marked by the "X." The lower part of Fig 6. shows a curve of merge points as a function of deflection (charge). The top of the merge curve is shown as a hollow point to make the point that this is the highest deflection at which merging occurs. The high charge on drops deflected beyond this point cause the drops to bounce, rather than merge. Obviously, a practical system must avoid operation near merge points, so a safe zone of operation exists to the left of the merge curves.

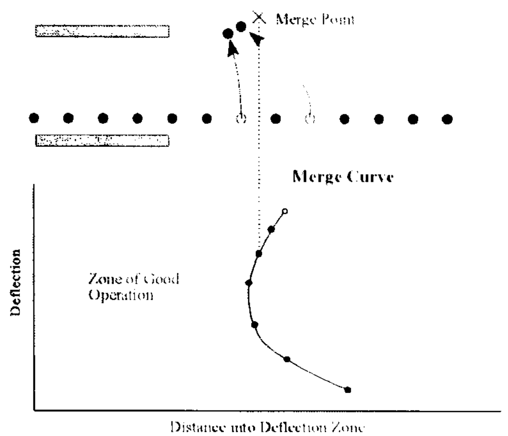

Figure 6.

With all the distortions inherent in CIJ multi-deflection technology, there are still thousands of rugged, industrial systems in use. These operate as character, rather than "bit map" printers. One of the tasks in the development of these printers is "compensation." This is the art of developing patterns of charging voltages which result in the printing of a character. In this process, often done on specially designed fixtures, the print patterns are developed by trial and error. The charge voltage pattern required to print an "S", for example, is significantly different than a simple set of voltages corresponding to the vertical raster.[5]. Several patents[6,7] have shown approaches to true bit map printers using multi-deflection technology. For various reasons, these have not become commercially viable, although they are capable of printing with excellent quality. In both these concepts, drops are deflected from the uncharged stream in both directions, using bi-polar charging. This minimizes the charge on the print drops, as well as their deflection. The smaller the deflection, the smaller the error in deflection. In the Crean[7] patent, sophisticated drop sequence algorithms were also used to spatially separate print drops to minimize interactions. Even so, complex drop compensation algorithms were required for excellent drop placement. In the Paranjpe[6] concept, only a few pixels were covered by each jet. The deflection was so small in this case that no compensation was required.

Continuous Binary Ink Jet

In continuous binary ink jet, as illustrated in Figure 1, one jet can only print a single line of pixels. To cover an image, two printer architectures are used; a drum printer and an array. In the drum architecture, a single jet (per color) is used to print on a substrate attached to a rotating drum. As the drum rotates, the image is printed in a "barber pole" stripe. With a single jet per color, the drum architecture is aimed at very high quality, rather than high speed. This follows from the numbers involved. A single jet can reasonably produce about 10^6 drops per second. An 8_ x 11" page at 300 pixels per inch contains 8.415 million pixels. If each of these is 5 bits deep[9] (zero to thirty one drops), the page contains just over 269 million drops. If the printer were 100% efficient, printing a page would require 269 seconds, or four and a half minutes. Thus, the speed capability of even a very high speed single jet is limited. The drum architecture is used by Iris Graphics, Inc. and others in just the manner described. It uses a 50 meter per second jet about one fifth the size of a human hair to print very high quality digital color. Since the drum architecture is conceptually more simple, emphasis here is placed on the binary array architecture.

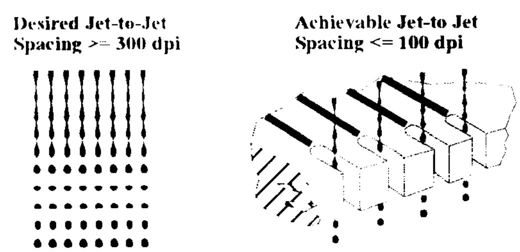

Figure 7.

In the array architecture, a linear array of jets spaced at the print resolution forms an electronic paint brush which creates an image on the substrate as it moves beneath the printhead. Two challenges are faced in binary array ink jet; forming straight, in-phase jets and charging them independently. Figure 7 illustrates the challenge. In conventional technology, the charging surfaces completely surround the break-off point of the jet to provide electrostatic shielding from external electrodes, such as the deflection electrode. The techniques involved, such as dicing slots in an insulating material and creating electrodes as illustrated on the right side of Figure 7, is limited to about 100 jets per inch for practical reasons. The desired spatial frequency is 300 jets per inch or even more.

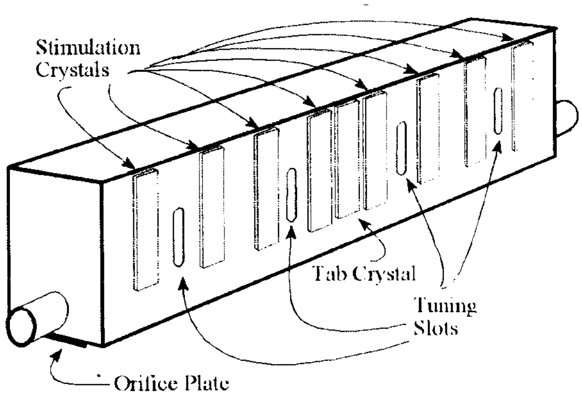

Figure 8.

The second challenge is to create the straight jets with uniform break-off as illustrated to the left of Figure 7. A good binary array CIJ system requires jet directionality of 3 mRad. The print jets are undeflected, so the drop placement accuracy relates directly to the jet directionality. Achieving the straightness is a very complex system engineering task, involving the quintessence of orifice plate, ink system and ink technology. Achieving uniform break-off, after the straightness is achieved is worthy of brief examination.

A key goal to simplify the driving electronics for the printer is to use the same charging phase for as many jets as possible. Ideally, one phase can be used for all jets. Changing the charging voltage from drop to drop can only be done at certain periods of time during the break-off cycle. If the charging voltage is changed just as the drop detaches from the filament, an intermediate level of charge can be obtained, a clearly undesirable situation. It is not possible to have the same phase for all the jets in an array. It is possible to create stimulation uniform enough for all jets to break-off in a narrow window of time within the drop generation cycle. This allows a phase "window of operation." We also want to operate in the no satellite "window" depicted in Figure 2, so the stimulation level must also be large.

The patent literature is literally full of inventions aimed at providing uniform break-off. Most of these inventions involve complex, difficult to assemble, non-reproducible systems. The system[8] shown in Figure 8, consists of an elongated metal bar, into which several features are machined. A cross feed hole is drilled through the bar for ink entrance and exit. A slot is created from the cross tube to the bottom face of the bar to supply ink

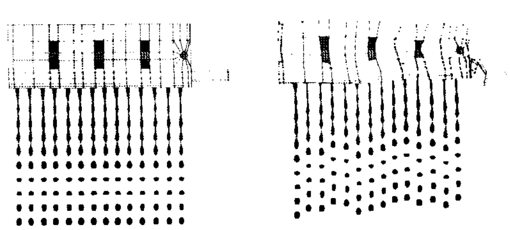

Figure 9.

to the orifice array. The orifice array is bonded to the bottom of the bar. At the outset, the concept was to create slots through the bar to suppress end to end vibrations. The thought was that a "pure" mode of vibration could be produced which moved the orifice plate "up and down." When the first prototype was fired up, the stimulation was anything but uniform. Whereas the goal was phase uniformity of $\lambda/4$, the uniformity achieved was about 4 λ. At this point in the development, invention ceased, and plodding meticulous science began. Figure 8 shows a finite element model of one of the first "resonators" to be tested. The model makes clear that the steel, is actually Jell-O at 100 kHz. Even the steel ink feed tubes are participants in the vibration. Ultimately, tight tolerances were required in the lengths of the tubes. Not shown in the "symmetrical" model in Figure 9 is a"teeter-toter" mode in the actual hardware. This asymmetric mode was so close to the desired mode that extremely tight tolerances were required on the parallelism of the feed tube and the bottom face of the resonator. Much of this development was Edisonian. Over one hundred resonator structures were fabricated with virtually every dimension of the device varied in a systematic fashion. Finally, a workable, manufacturable device emerged.

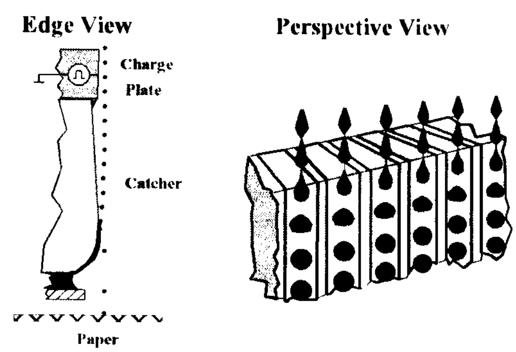

Figure 10.

Given the ability to make the parallel rows of drops at high resolution, it is still necessary to devise a charging system to deal with such a close array. This was achieved[10] with the "flat face" charging configuration shown in Figure-10. In this implementation, a multiplicity of conducting strips is placed on a flat charging structure, one corresponding to each jet. The jet array is placed in close proximity to the charging strips. In this way, the primary electrostatic influence on each jet is its own charging electrode. This is illustrated on the right side of Figure 10.

There are three critical aspects of this invention. First, there is no deflection electrode in this configuration. Each charging electrode performs both charging and deflecting functions. As a result, deflection in this system is a square law function of drop charge. Although the combination of the neighboring electrodes can have a 30% impact on the charge of a drop, the impact on drop deflection is only 9%.

The second critical aspect is that deflections are very small. The catcher has essentially a flat vertical surface with a slight outward "positive slope." Catch drops are deflected only three or four diameters into impact on the catcher face. They skid along the catcher forming a fluid film which is carried away by vacuum. This is illustrated on the left side of Figure-10, which is approximately to scale. The result is a system with very tight tolerances, but high print quality.

The third critical aspect of this configuration is the throw, or distance from drop formation to impact on the substrate. Previous devices using slot or tunnel charging used a drop throw of an inch or so. In this system, the drop throw is about half that amount. Therefore, the 9% deflection error has a negligible effect on print quality in most cases. When the highest quality is required, other techniques are used to make the error even smaller. The resulting system is able to print with good quality at 1000 feet per minute. This clearly makes this printhead technology the worlds fastest digital printing system.

The Future of CIJ

Continuous ink jet applications continue to grow, many years after some pundits predicted that the technology had limited applicability. Because of the ink handling and recirculation systems required for CIJ, it is inherently more expensive than drop on demand systems. However, the ruggedness afforded by pressurized system makes it ideally suited for heavy duty industrial use. Today, multi-deflection systems are used to print serial numbers on cold, wet beer cans as they are produced. "Use by" dates are printed on an extremely wide variety of products. Thermochromic inks print codes on canned foods which are subsequently baked to kill botulism. If the correct time and temperature is used for baking, the ink changes color, providing a new level of food safety. These applications continue to grow, spurred on by the cancerous growth of government regulations. Although these systems are largely limited to orthographic characters, their print quality continuous to improve dramatically. The large electronic content of the devices insures that the cost will decline.

Binary array printers are increasingly used in a wide variety of applications, from mass mail to billing. The worlds largest phone company, NTT, is in the process of converting to binary ink jet printing in it's billing operation for several reasons. The reliability of the systems allows them to print 8,000 miles of document between printhead refurbishments. The cost per image is less than half that of electrophotography. The print speed of 600 feet per minute and the ability to easily print color documents allows new flexibility in the billing application. As print quality improves, and cost declines, the ability of CIJ to compete in the industrial market can only improve.

Summary

This has been a very brief examination of some of the interesting aspects of CIJ technology. The history effects which arise in the charging and deflection processes were discussed, and some of the limitations of multi-deflection CIJ were considered. New binary array CIJ technology was discussed from the point of view of higher resolution capability.

Acknowledgments

The author is indebted to many co-workers over the years who have helped educate him. Especially noted are Mr. Richard Sweet, who invented this fascinating technology. Sadly missed is Ken Fischbeck, who was a true pioneer in the drop on demand arena.

References

1. J. W. S. Rayleigh, Scientific Papers, Vol. 1, Cambridge University Press, London, p. 361 (1899)
2. C. Weber, Ziets. Fur Angewandte Math. Und Mechanik 11, p. 136 (1931)
3. W.T. Pimbley and H.C. Lee, IBM J. Res. Develop. 21, #1 p. 24 (1977)
4. G.L. Fillmore, et al, IBM J. Res. Develop. 21, #1 p. 38 (1977)
5. W. L. Buehner, et al, IBM J. Res. Develop. 21, #1 p. 5 (1977)
6. S. Paranjpe, U.S. Pat. # 4,219,822 (1980)
7. P. A. Crean, et al U.S. Pat. # 4,395,716 (1983)
8. W. L. Wood, et al U.S. Pat. # 4,999,647 (1991)
9. C.H. Hertz, et al U.S. Pat. # 4,620,196 (1986)
10. D.A. Herron U.S. Pat. # 4,636,808 (1987)