INK-JET-PRINTING: THE PRESENT STATE OF THE ART

Wolfgang R. Wehl
Siemens AG, KWT TD 33, Rohrdamm 7,
1000 Berlin 13, West Germany

Abstract

Drop-on-demand ink-jet printers are more suitable than any other type of printer for installing directly alongside a PC in an office. There is a very good reason for this, in that ink-jet technology has a considerable number of advantages: You get best print quality with high reliability. Moreover ink-jet-printers are unbeatable silent and have low manufacturing and consumption costs. No other printing principle allows color with such simple means.

This paper will give you an overview to the present state of the art of drop-on-demand ink-jet printing. We discuss the different actually manufactured ink-jet print heads with piezoelectric and thermoelectric transducers. The respective advantages and disadvantages and the fundamental limitations will be illustrated. Finally essential parts are dedicated to subjects like ink, paper, cleaning and sealing mechanisms.

1. Ink-Jet Printers and their Applications

In recent times a range of printers has been growing steadily in popularity among users - the ink-jet printers. This paper will give you an overview to the present state of the art of drop-on-demand ink-jet printing. According to market research carried out by Dataquest (Fig. 1), there will be a 400% increase in the number of ink-jet printers sold per year between now and 1992 in Europe alone, taking the sales figures to 1.5 million units, and 0.3 million units for color printers. There is a very good reason for this, in that ink-jet technology has a considerable number of advantages. But more of that later.

Like thermo, thermal-transfer and electrophotographic printers, ink-jet printers belong to the non-impact-printers (Fig. 2). The first one was called the Mingograf, has been around since 1952 and ejected a continuous stream of ink from a directable hairpin nozzle. It works in a medical recording machine manufactured by Siemens-Elema in Sweden. Regardless of the principles, techniques or even technologies involved, all ink-jet printers eject droplets of ink with a diameter usually less than 100 μm on to paper or transparencies. As you can see from the list of advantages and disadvantages below, ink-jet printers are suitable not only for conventional office applications but particularly for the increasingly important areas of desktop publishing (DTP) and CAD/CAM.

Advantages of Ink-Jet Printers (Drop-on-Demand-Types only)

- Matrix printing allows any characters or graphics to be formed
- Resolution up to 600 dpi (= 24 lines/mm = 1 ppm)
- Almost silent printing (10 - 35 dB(A) print head noise)
- Few moving parts, hence high reliability
- High print speed
- Low consumption and manufacturing costs
- Color printing feasible at low cost and high quality
- No wear and tear (or only very little wear and tear in the case of bubble-jet printers)
- Large paper formats can be handled (A2 for example)
- Extremely low power consumption

Disadvantages of Ink-Jet Printers

- Multiple copies not possible
- With the exception of the hot-melt method, the print quality depends to some extent on the paper used but excellent results can now be obtained using standard office paper (plain paper).

In ink-jet printing a basic distinction is made between the continuous-jet principle and the drop-on-demand principle. Continuous-jet printing systems, which will be not discussed in this paper, are used especially in the field of marking and coding. There are various...
ways of producing ink droplets on demand. Two types of actuator have now become established on the market in almost equal shares - print systems with piezoelectric transducers and those with thermoelectric transducers.

Drop-on-demand printers are no longer than conventional dot-matrix printers and are basically no more expensive to manufacture. The fact that they can print at high speeds does not mean they are more powerful than other types of printer for installing directly alongside a PC in an office. Systems are available with anything from four to 60 nozzles and many can print in color or transparencies. Resolutions range from 72 dpi to 400 dpi. Owing to their low power requirements they can be used as laptop printers, as models from Hewlett-Packard and Diconix illustrate. Ink-jet printers with thermoelectric transducers are produced by Hewlett-Packard and Canon, while printers with piezoelectric transducers are produced by Canon, Dataproducts, Epson, Sharp, Tektronix and, last but by no means least, Siemens.

2. Technical description of the drop-on-demand technologies

In the main part of this article I would like to take a closer look at the technical design of the various types of ink-jet printer already mentioned and point out the advantages and disadvantages of each technique used and their physical limitations. As already mentioned (see Fig. 2) drop-on-demand ink-jet printers can be divided into two groups according to the types of electro-mechanical transducers they use: systems with piezoelectric transducers (piezo-jet printers) and systems with thermoelectrical transducers (bubble-jet or thermo-jet printers).

2.1 Print Mechanisms with Piezoelectric Actuators (Piezo-Jet)

Up to 1984 the only ink-jet printers available on the market in addition to the continuous-jet versions were piezoelectric drop-on-demand printers. Fig. 3 shows how these printers can be divided into three categories according to how their transducers operate and how they are arranged. The third category is a very recent addition.

1. Thickness and radial resonators with piezo-tubes by Zoltan
2. Flexural resonators by Stemme (side shooters) or Kyser (edge shooters) (piezo-diaphragm systems)
3. Longitudinal resonators with piezo lamellae by Howkins

Each of these has its advantages and disadvantages, but common to each - despite the high pulse voltages - is the low power requirement of between 0.5 µl and 9 µl per ejected droplet. In view of the different efficiencies of the systems it is difficult to avoid adjusting for the individual nozzles. With piezo systems it is possible to achieve maximum interruptible ejection frequencies of over 10 kHz. Generally speaking, the ejection frequency is inversely proportional to the size of the transducers and the ink chamber. Let's turn our attention now to the different techniques.

2.1.1 Print Mechanisms with Piezo-Tube Systems

Since Siemens in particular, together with the Institute for Precision Engineering at the Technical University of Munich, has carried out intensive research and development work on ink-jet printers with piezo-tube actuators and has manufactured hundreds of thousands of them we have a great deal of precise data at our disposal, so I would like to take a fairly detailed look at the way in which these ink-jet printers work.

As we can see in Fig. 4, an ink-jet mechanism with piezo-tubes consists of only three major parts: the piezo-tubes, the ink channels and finally the nozzles. So far we have been able to accommodate as many as 32 separate systems into a single print mechanism, the PT90 from Siemens. This gives a resolution of 240 dpi (9.4 lpm) and, at an ejection frequency of 4.8 kHz, a print speed of 200 cps in letter quality (LQ) mode and 400 cps in near letter quality mode (NLQ).

In addition to the central functional elements, an ink-jet mechanism such as this has a number of other parts, notably the seal mechanism which closes off the nozzles when the printer is switched off and thereby ensures that ink does not dry up and clog the nozzles even if the printer is not used for long periods. The seal mechanism also acts like wiper-screen wipers to keep the nozzles clean.

In Siemens machines, as in other ink-jet printers (including those from Hewlett-Packard, for example), the ink cartridge is mounted on the print head and moves along the carriage with it. Some manufacturers such as Canon and Epson favor a stationary ink cartridge. In this case a long heavy-duty hose must be provided between the cartridge and the print head and a buffer chamber incorporated in the print head. The ink passes through a filter into the actual nozzle head where it is distributed among the individual channels.

Function of an Individual System with Piezo-Tubes

As I have already mentioned and as shown in Fig. 5, an individual system consists of a piezo-tube, channel and nozzle. Since the free surface of the ink in the chamber is always lower than the lowest nozzle there is a small static underpressure in the channel. In the state of rest the ink is held in the nozzle by capillary force so that no ink flows out of the open nozzle.

2 - 47
If a droplet is to be ejected an electrical pulse must be applied to the transducer. Depending on the system used, voltages of between 60 and 200 V are needed for piezo actuators. From the electrical point of view, the piezo element acts in much the same way as a capacitor, the difference being that voltage pulses cause the internal cross-section of the tube to contract or expand. This takes place very quickly indeed, so fast that the ink cannot flow immediately into or out of the resultant differential volume.

The result is local overpressure or underpressure which can be interpreted as sound waves in liquid. These waves disperse in the channel in accordance with the laws of acoustics, which means, for example, that owing to the increase in cross-section at the open end of the channel the waves are reflected with phase reversal. This is a simple way of creating bipolar pressure distributions from unipolar pulses. It also retains the energy within the channel and so prevents cross-talk. In order for droplets to be formed, the pulse, geometry, materials and ink must of course be carefully matched.

In the nozzle the pressure waves accelerate the ink meniscus and cause a droplet to be ejected. The timing of this process is shown in the sequence of diagrams in Fig. 6 which have been produced with the aid of an acoustic finite element program. A partial vacuum first draws the ink back (to gather itself for action, so to speak) and then a wave of overpressure ejects the droplet before a further partial vacuum puts a brake on the ink meniscus and settles the system for the next droplet. A trick film has been made showing the entire process, which in real life lasts barely 200 ps; this visual presentation makes the sequence of events much easier to follow. Pressure dispersion, meniscus movement and droplet formation are based on a computer model developed by the Faculty of Precision Engineering at the Technical University of Munich.

2.1.2 Print Mechanisms with Piezo-Diaphragm Systems

Piezo-diaphragm systems operate on exactly the same principles as piezo-tube ink-jet mechanisms, except that the pressure waves are produced by the flexural movements of a plane piezo disk on a rigid diaphragm. Imagine it to work in much the same way as a bimetallic strip. Voltage pulses cause the diameter of the piezo disk to change in the sub-micron range. Since the rigid metal diaphragm prevents such movement there is a positive or negative arching of the entire unit of approximately 1 μm.

The Epson piezo-diaphragm system shown in Fig. 7 and used in the SQ-2500 model ejects ink droplets around the edge - hence the name edge shooter. As in the case of piezo-tube systems, this system needs relatively long ink channels, which in turn restricts the maximum ejection frequency of these Epson ink-jet print heads to 3 kHz. On the other hand, in edge shooters the nozzles can be very closely packed - we shall also see this with the bubble-jet systems. The SQ-2500, for example, with its 180 dpi print head has two rows with a pitch of 90 dpi (282 μm). The nozzle area in this print head is only about one millimeter wide and four millimeters high, which simplifies the tasks of controlling and accurately positioning the droplets and cleaning and sealing the nozzles when not in use.

2.1.3 Print Mechanisms with Piezo-Lamellas

The print mechanisms from Dataproducts (Exxon) also operate with piezo actuators. In this case, however, there are many piezo lamellas arranged in parallel (Fig. 8) which extend or contract when subjected to voltage pulses. This movement is again transferred to an ink chamber and an ink droplet is ejected as a result. This technique combines the dual advantage of the close nozzle packing of the edge shooter and the high ejection frequency made possible by a small ink chamber.
The Dataproducts ink-jet mechanism differs from its competitors in several ways. The Dataproducts' printer ejects a wax-based ink mixture, which is dissolved in a solvent. This is different from the ink used by other printers, which are typically based on ink jets that contain dyes dissolved in a solvent mixture.

An important aspect of the Dataproducts mechanism is its ability to maintain a constant temperature throughout the printing process. The printer head, including the ink supply lines and the ink cartridge, is maintained at a temperature of around 100°C. This helps to avoid problems associated with ink drying up in the nozzle, even though the wax solidifies as soon as it comes into contact with the paper. However, I shall not at present go into any further detail about the necessary characteristics of inks and their relative advantages and disadvantages; this information is contained in Section 3.1.

2.2 Print Mechanisms with Thermoelectric Actuators (Bubble-Jet)

Over the last few years piezo-activated ink-jet mechanisms have come under competition from bubble-jet systems. Despite some drawbacks in terms of performance they do have some advantages, but before we take a look at these advantages let's first see how a bubble-jet system works.

How a Bubble-Jet System Works

Bubble-jet systems can be classified as either edge shooters or side shooters. The basic patent taken out by Canon relates to the edge shooter principle. In Fig. 9 shows an elongated channel in the bubble-jet system. Instead of the piezoelectric transducer there is a heating element behind the nozzle. As Fig. 10 shows, the dimensions are much smaller by comparison. The channel is only about half a millimeter long and so narrow that the nozzles can already be arranged only 60 μm apart (= 400 dpi).

Fig. 8 Piezo-lamella system from Dataproducts (Exxon)

Fig. 9 Schematic diagram of a bubble-jet system (edge shooter)

Fig. 10 Comparative sizes of ink-jet actuators

Fig. 11 shows the relative timings for droplet formation in the bubble-jet and piezo-diaphragm systems. In the bubble-jet nozzle a short 7 μs long pulse (50 μs) applied to the heating element produces a small vapor bubble in the ink above the element. The bubble drives ink out of the nozzle with great force and then collapses approximately 50 μs later, cutting off the jet of ink. In contrast to piezo systems, in which the defined oscillation of the actuator causes the ink to move, the bubble-jet principle relies solely on capillary action to draw the ink into the nozzle. Depending on the mass of the droplet, this takes at least 250 μs and is the reason why the current maximum ejection frequency is restricted to "only" around 4 kHz.

Piezo-Diaphragm Bubble Jet

Fig. 11 Droplet formation with piezo-diaphragm and bubble-jet systems

Since bubble formation does not produce the optimum pressure distribution, as is the case with piezo actuators, the ink jet splits up into individual droplets after it has left the nozzle. However, these droplets have a very high flight speed (> 4.5 m/s) and hit the paper as a single dot at print speeds of less than 120 cpi and a nozzle-to-paper gap of 1 mm. The print quality is the same as that from a laser printer costing three times as much - as you can see from this article which was produced on a 300 dpi bubble-jet printer.

Manufacture of Bubble-Jet Mechanisms - The Cost Factor

The crucial advantage of ink-jet mechanisms based on thermoelectric transducers is that they can be manufactured using procedures taken from semiconductor technology. The print heads are built up on silicon wafers by sputtering, evaporation, etching and similar processes, with the structures produced by mask exposure. Only in this way can the required structural tolerances in the micron range be achieved. Owing to the small dimensions the entire manufacturing process has to take place in clean rooms, but it does lend itself to automation. Since the nozzles are very small it is possible to accommodate almost 40 heads on a single 4-inch wafer.

Although initial investment costs are high these print heads are relatively cheap if produced in sufficient quantities. An additional factor is that the value of the heating resistance (currently around 60 - 90 Ω) is freely selectable and so the control voltage can be low. Despite the more modest efficiency of this system, compared with piezo systems, the simple square pulse form and the fact that there is no need for in-
individual matching of the nozzles combine to cut the cost of electronic circuitry to a minimum.

2.2.1 Bubble-Jet Mechanisms of Edge Shooter Design

To date, Hewlett-Packard and Canon are the only two manufacturers of bubble-jet printing systems. Canon has opted for the edge shooter design already described above. As the sectional view of the Canon head shows (Fig. 12), this arrangement has the advantage that the nozzles can be placed directly alongside each other in an extremely narrow pitch.

So far Canon has managed to pack 128 nozzles in a single print head, giving a resolution of 400 dpi. Fig. 13 shows a selection of ink-jet mechanisms from Canon. A particularly interesting development is the 200 dpi color printer which instead of a print head has four rows of nozzles, with each row containing 1792 nozzles. The machine can print 31 pages per minute.

2.2.2 Bubble-Jet Mechanisms of Side Shooter Design

Shorter ink channels and better ink flow can be achieved with the side shooter principle. Fig. 14 shows a schematic diagram of the Hewlett-Packard print mechanisms. These are at present available in resolutions of 90 dpi (12 nozzles), 180 dpi (30 nozzles) and 300 dpi (50 nozzles). In side shooters the heating element is positioned directly behind the nozzle. In contrast to edge shooters a nozzle plate is needed, though this is not necessarily a disadvantage. Otherwise, the two bubble-jet systems function in the same way. Each nozzle of course needs a little more space, which means that in the 50-nozzle DeskJet print head the nozzle area is 5 mm by 3 mm.

2.3 Technical Data of Drop-on-Demand Systems

To round off this technical description I should now like to set out the technical data of the drop-on-demand ink-jet systems so that you can make direct comparisons.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Piezo Systems</th>
<th>Bubble Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>ejection frequency/kHz</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>flight speed/m.s⁻¹</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>maximum achieved</td>
<td>240</td>
<td>180</td>
</tr>
<tr>
<td>vert. resolution/dpi</td>
<td>97</td>
<td>115</td>
</tr>
<tr>
<td>pulse voltage/V</td>
<td>150</td>
<td>60-170</td>
</tr>
<tr>
<td>typ. transducer value</td>
<td>800pF</td>
<td>550pF</td>
</tr>
<tr>
<td>energy/droplet/pJ</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>manufacturing costs</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>electronic complexity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>adjusting</td>
<td>individ.</td>
<td>none</td>
</tr>
<tr>
<td>lifespan (characters)</td>
<td>10⁶</td>
<td>10⁸</td>
</tr>
<tr>
<td>print speed</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>(LQ, 10 cpi)/cps</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Technical data of drop-on-demand ink-jet systems.
3. Miscellaneous

As regards the print quality and reliability of ink-jet printers, the ink and paper used, and even the design of the cleaning and sealing mechanisms, are playing an increasingly important role.

3.1 Ink and Paper

The only real similarity between the ink we use in our fountain pens and the ink used particularly in drop-on-demand ink-jet printers is that they are both liquid and both contain dyes. Refilling an ink cartridge with ink that has not been expressly approved by the original manufacturer is almost invariably fatal. The ink-jet mechanism gets clogged up and is generally impossible to repair. This is because the ink and the print mechanism have to be closely matched over a great many parameters. The requirements that the ink has to meet are stringent in the extreme, as the following list clearly illustrates:

Requirements Governing Inks for Ink-Jet Mechanisms

The ink must:
- be compatible with the materials used in the print mechanism;
- not leave any deposits in the channels or on the nozzles;
- not contain particles or other contaminants;
- not dry in the channels;
- be suitable at storage temperatures between -25 and +70 °C;
- comply with defined values for density, viscosity and surface tension at temperatures ranging from 10 to 40 °C;
- not separate out;
- not contain bacterial growths or algae.

In addition, the ink for bubble-jet mechanisms must:
- permit clean, defined bubble formation without leaving deposits;
- be resistant to temperatures of up to 350 °C for short periods.

Requirements Governing Inks with Respect to the Paper Used

The ink must:
- produce optimum print quality on standard uncoated office paper;
- be quick-drying, even for solid color graphics;
- provide maximum contrast and contain the best dyes for the particular application;
- not produce frayed edges;
- be water-resistant, non-fading and indelible.

Other Requirements

The ink must be:
- non-toxic;
- chemically neutral;
- not inflammable.

These lists indicate clearly why manufacturers of ink-jet printers spend a great deal of time and money on developing inks, particularly as a number of these requirements are to some extent mutually exclusive. At present all suppliers are striving to achieve optimum print quality with their inks on normal uncoated, plain paper.

Drying Properties of Ink

It is no easy matter to have the ink dry quickly on the paper so that it is smudge-proof and water-proof without it penetrating the paper too much. If this happens the print quality and the contrast suffer since the individual droplets tend to have frayed edges. Different manufacturers have come up with different solutions to this problem.

Epson is working with a reactive highly alkaline ink but there are only a few types of paper which give optimum print quality. In its extremely fast DeskJet model, Hewlett-Packard moves the paper to a holding tray so that the ink has a long time in which to dry. Canon, on the other hand, heats the paper in its BJ-130 printer so that the water in its extremely aqueous ink quickly evaporates. As yet, none of these methods is entirely satisfactory for solid graphics, which is why we have yet to see a color ink-jet printer which will work with normal paper.

As I have already mentioned, the liquid wax ink used in Dataproducts' printers differs fundamentally in certain aspects from other inks. Since its normal state is cold and solid, problems of drying in the print mechanism and on the paper simply do not exist. The fact that the liquid wax solidifies immediately it comes into contact with the print medium means that the print quality is virtually unaffected by the type of paper used. There is a problem, however, in that the wax is not entirely scratch-resistant and may show signs of cracking: printouts are also not sufficiently heat-resistant.

3.2 Cleaning and Sealing Mechanisms

Often neglected in the early days of ink-jet printers, cleaning and sealing mechanisms improving the reliability nowadays make all the difference between the success or failure of an ink-jet printer on the market. If you pack a large number of small nozzles closely together there is always the danger that dirt will block one or more of them or that air bubbles will get into the ink channels. As a result the nozzle will either reject ink at an angle or not eject ink at all.

To prevent this from happening, or to ensure that the user is unaware of it happening, modern ink-jet printers have facilities for cleaning the print mechanism at regular intervals, and, even if the worst came to the worst, the user can always press a button to start an extended cleaning procedure. The cleaning systems work by drawing ink and air bubbles out of the channels; they can even fill a completely empty print head with ink if need be. They then wipe the nozzle surface clean. Fig. 16 shows a schematic diagram of the cleaning facilities of the Epson SQ-2500 printer:

Another function of this mechanism is to seal the nozzles whenever the printer is not in use or is switched off. This prevents the ink drying in the print mechanism. Thanks to these measures an ink-jet printer can now achieve a mean time between failures (MTBF) of 5000 hours of operation so even a high-volume user can expect trouble-free operation for more than five years.

4. The Future

To sum up, we can state that as yet all ink-jet printers are starting to take the market by storm. By the mid-1990's there may well be more ink-jet printers than any other type of printer. The reasons for this prediction are fairly convincing:

Ink-jet printers are ideal for desktop use since they are quiet and extremely economical. For only 30% of the investment cost of a laser printer, or less, it is possible to achieve a print quality which is every bit as good. The problems of reliability which often beset ink-jet printers in the past have now been completely eradicated thanks to sophisticated cleaning and sealing mechanisms.

If you want to print in color - and there will be many in the near future who will - you will need an ink-jet printer. No other system can print in color at such reasonable cost without trade-offs in terms of color brilliance, print quality or print speed.
Owing to their modest power requirements and their compact design, ink-jet printers are ideal for battery-powered mobile applications in conjunction with laptop computers.

There are basically no restrictions on the maximum print format, as is the case with laser printers. An extreme example is the Matsushita Jumbo Ink Jet which can print an area of 7 m by 16 m (137 sq ft) in 11 hours.

Development of ink-jet printing will continue. Soon there will be printers capable of resolutions of 400 dpi and more. And ink will find applications in a great many new areas such as fax, video printers, point-of-sale printers and card printers. Ink-jet printing has a very promising future.

5. References