Photorealistic Ink-Jet Printing Through Dynamic Spot Size Control*

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A method has been developed for dynamically modulating the drop volume created by an array piezoelectric drop-on-demand ink-jet printhead. A 4:1 range of volume modulation has been achieved, resulting in approximately a 4:1 range in printed spot area. The modulation is continuous (i.e., not discrete) over a significant part of the total range, and it is achieved with a minimal decrease in throughput. Optical densities for modulated spots have been measured at 300 and 600 dpi for several printhead configurations. Algorithms have been designed to use a combination of continuous modulation and halftoning (using modulated drops) to produce photorealistic images.

Journal of Imaging Science and Technology 40: 390–395 (1996)

Introduction

In the past five years, drop-on-demand ink-jet printers have come to dominate the low-end printer market. The transition of ink-jet printers to color has both accelerated this trend and created new markets. With the emergence of color, image quality has assumed a new importance. The principal factor limiting image quality in most office printers, including ink-jet printers, is the use of fixed spot size and spot intensity. Users can look at a wide dynamic range of spot intensities on their CRT screens, but cannot easily and inexpensively print them.

Thermal ink-jet printers do not readily lend themselves to drop volume modulation because of the almost binary nature of their droplet formation process. Concepts for multiple heating elements have been proposed, but have not been demonstrated and would lead to a significant increase in complexity. Most piezoelectric ink-jet printers can easily modulate drop volume, but drop velocity is coupled with drop volume. These velocity variations cause placement errors. In addition, the easiest way to modulate drop volume, via voltage modulation, is costly to implement in the drive electronics. Finally, both thermal and piezoelectric printers can modulate spot volume by printing multiple drops per spot. However, either the printer throughput must decrease from what could be achieved using a single drop per spot, or the number of orifices must increase significantly.

Through a combination of printhead design and drive waveform modulation, Compaq Computer Corporation's array piezoelectric drop-on-demand ink-jet printhead technology[1–3] can achieve drop volume modulation with a minimal decrease in throughput and in a cost-effective manner. In addition, unlike systems using only multiple drops per spot, the modulation is continuous (i.e., not discrete) over a significant part of the total range.

Printhead Description

Fabrication. The Compaq drop-on-demand array printhead technology was derived from manufacturing processes that can be scaled to large-volume, low-cost production. The fabrication process for the specific design utilized for the spot size modulation experiments is described briefly below.

As illustrated in Fig. 1, piezoelectric material (usually lead-zirconium-titanate, or PZT) is prepared initially in a standard fashion: A large rectangular block is formed and a temporary metallization is applied to two sides of the block. A high voltage is then applied across the two metallization layers to orient the piezoelectric properties of the material. This process is referred to as *poling*. At this point, the preparation of the material departs from standard processing. Because the Compaq design uses the piezoelectric material in shear mode (as explained below), the poling metallization must be removed. The block of piezoelectric material is then sliced into rectangular pieces that will be formed into individual printheads. These pieces are much larger in two of their three dimensions: $25 \times 25 \times 8$mm and $20 \times 25 \times 0.25$ mm being typical for this design, where the former is referred to as the "bottom" PZT and the latter is referred to as the "thin" PZT. Metallization is applied in a batch (i.e., multiple parts at the same time) deposition process to the two large surfaces of both the bottom and thin blocks. This is the functional metallization that will be used to actuate individual jets.

Next, a bottom and a thin block of piezoelectric material are laminated together with electrically conductive epoxy, such that their poling directions are aligned. This "sandwich" structure is then machined with a precision diamond saw, creating both fluid channel openings and channel actuator structures. Figure 2 illustrates the laminating and sawing operations. The channel and wall widths for the devices used in the study presented here were 85 μm, and channel depth/wall height was 360 μm. Configurations have been fabricated and tested with channel widths from 40 to 170 μm. The channels are sawed the entire length of the piezoelectric block (25 mm). The printheads used for the spot size modulation studies had 16 channels. Printheads with 120 channels were the "standard" design used to develop the manufacturing processes. Devices with up 240 channels have been fabricated.

The tops of the ink channels are created by attaching a cover plate to the machined sandwich structure. The cover plate is solid except for a region that has been machined to form a fluid manifold.

Original manuscript received March 11, 1996. Revised August 5, 1996.

* Presented in part at IS&Ts 11th International Congress on Advances in Non-Impact Printing Technologies, October 29–November 3, 1995, Hilton Head, South Carolina.

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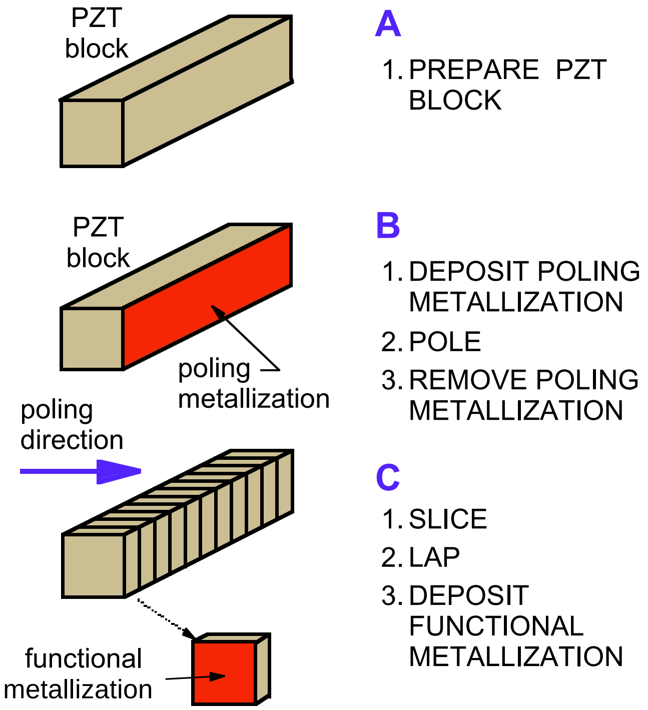

Figure 1. Print head fabrication process: piexoelectric material preperation.

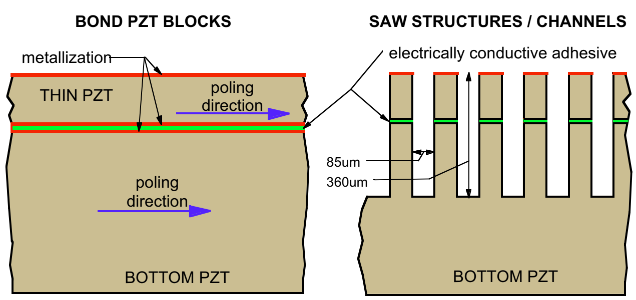

Figure 2. Printhead fabrication process: bonding and sawing.

An excimer laser ablation process is used to machine 120 precision orifices into a polymer film that attaches to one end of the printhead. The orifices are machined to align to the ink channels when assembled. For this study, the orifices were machined before attaching the polymer film to the piezoelectric structure, because this procedure produces the highest quality orifices. The backs of the channels are sealed with an acoustic-energy-absorbing polymer. Figure 3 illustrates these process steps.

When the sandwich structure is formed, the lower piezoelectric block is longer at the rear (i.e., the surface opposite from the orifice plate) of the printhead, thus leaving a metallization layer exposed. The sawing process thus creates individual metallized bonding pads. A flex circuit is attached to these pads, allowing the metallization layer in the middle of each channel wall (i.e., the actuator) to be individually addressed electrically. The metallization layer at the top of each wall is electrically connected to a common potential through the cover plate metallization. In the final assembly operation, the other end of the flex circuit is attached to the drive electronics.

Actuator Operating Principle. Figure 4 illustrates the actuator operating principle of the printhead. Each ink channel requires its two walls to move in opposite directions to create the pressure waves that cause a droplet to be ejected. This wall motion is accomplished by placing equal and opposite voltages on the inner electrical layers of each wall while holding the metallization layer at the top of both walls at ground. This treatment creates equal and opposite uniform electrostatic fields in the upper sections of the two walls (formed from the thinner of the two piezoelectric blocks). Because this field is at a 90° angle to the poling field, the upper wall sections deform in shear mode,[4] and the middle of each wall is displaced outward from the channel being actuated.

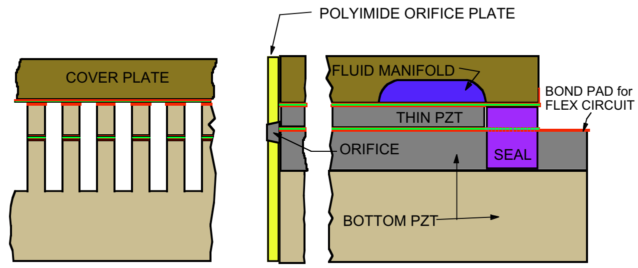

Figure 3. Printhead fabriction process: cover and orifice plate attachment, and channel sealing.

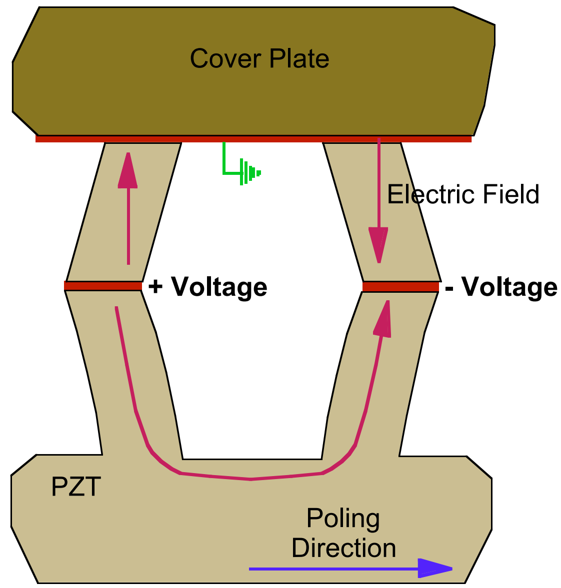

Figure 4. Printhead operating principle: simple and complex fields generate a primarily shear mode motion.

The electric field in the lower section of the walls and in the floor of the channel originates in a much more complex fashion. If an ink is used that is electrically nonconductive, or if an insulating layer is used to coat the channels and a conductive ink is used, a significant electric field will be established in the nonconductive ink or in the insulating layer. However, because the dielectric constant of most “soft” piezoelectric materials (e.g., PZT) is 3 to 4 orders of magnitude greater than that of typical fluids and insulating materials,[5] almost all of the electric displacement (the product of field times dielectric constant) will be confined to the piezoelectric material. Thus, a strong field/displacement will be established between the inner metallization layers of the two walls through the floor of the ink channels, as shown in Fig. 4. This complex U-shaped field creates a mostly shear mode displacement in the bottom section (below the inner metallization layer) of each wall, again causing the middle of each wall to be displaced outward from the channel being actuated.

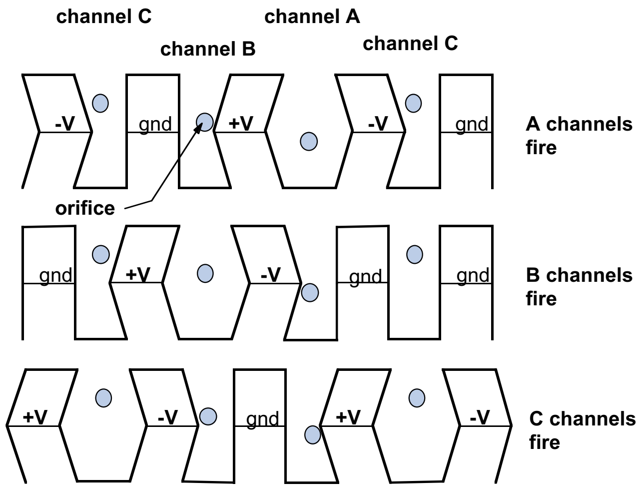

Figure 5. Multichannel operation for channels with common walls.

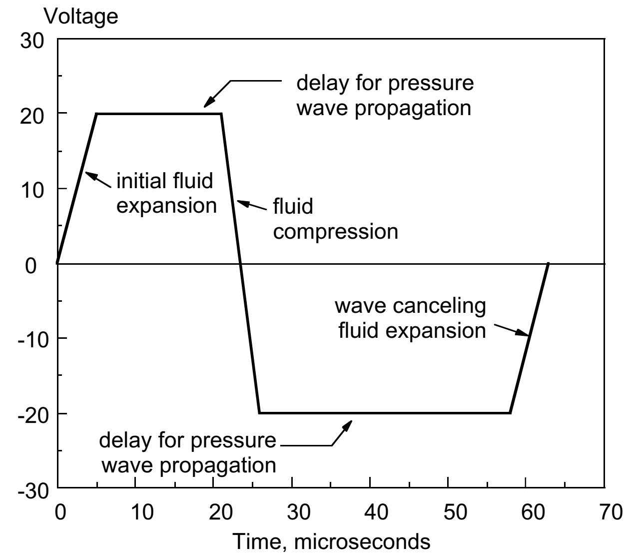

Figure 6. Typical bipolar drive waveform.

The portion of the U-shaped electric field in the floor of the channel is parallel to the poling field. This causes the channel to widen and the floor to drop when the field is applied. Thus, all parts of the motion of the two walls act to increase the cross-sectional area of a channel when equal and opposite voltages are applied to the inner metallization layers of the two walls. This change in area is what creates the pressure waves that lead to ejection of a droplet.

Multiple Channel Operation. Because adjacent ink channels have a common wall, no two adjacent ink channels may be actuated at the same time. Conceptually, every other ink channel could be actuated simultaneously and the array could be divided into two groups of channels (even and odd) that would alternate printing. All of the printing using Compaq printheads, including all the spot size modulation experiments, was accomplished by using three groups of jets, allowing only every third jet to be actuated simultaneously. This is illustrated in Fig. 5. This "firing order" reduces the acoustic crosstalk caused by using common walls. For the printhead to be able to produce a straight line from spots printed by adjacent jets, the orifices are staggered, as also shown in Fig. 5, to compensate for the ejection time difference between adjacent jets.

Volume Modulation Methods

The ink channels formed by precision sawing are 2 to 3 orders of magnitude longer than they are wide and deep: 20 mm versus 85 and 360 μm, respectively. Thus, the ink channels behave like an "organ pipe" resonator[6,7] when energy is input by actuating the channel walls. This behavior determines the drive waveform used to eject a droplet and the method used to modulate drop volume. A typical drive waveform is shown in Fig. 6. The initial voltage rise creates an expansion wave in the fluid. The voltage is held at the maximum value until the expansion wave reflects from the channel/manifold interface as a compression wave and becomes centered in the fluid channel. The voltage is then driven to an equal magnitude negative value to reinforce the compression wave. This reinforced compression wave propagates to the orifice and causes a droplet to be ejected. At some later time, the voltage is returned to ground. A bipolar waveform was originally selected for the Compaq printhead technology because each wall must be driven by one waveform to address the ink channel on one side, and by the same waveform inverted to address the ink channel on the opposite side. A bipolar pulse thus minimizes the overall voltage requirement.

The final return to ground generates another expansion wave and can be used to cancel undesired acoustic oscillations that occur in the ink channel after a droplet is ejected. To accomplish this, the second delay (between voltage fall and return to ground) is roughly twice that of the initial delay (between voltage rise and voltage fall) for a device that has the entire channel driven, as is the case for the Compaq printhead. If the second delay is then decreased significantly, the expansion wave created by the return to ground can be made to cancel all or part of the compression wave that causes droplet ejection. By thus changing the time that a compression wave is "resident" at the orifice, the volume of the droplet ejected can be changed. Because the droplet velocity is determined to first order by the magnitude of the pressure wave, modulating the second delay allows droplet volume to be modulated with less effect on droplet velocity than with other methods (i.e., voltage modulation or pulse width modulation of a unipolar pulse). Timing (or pulse width) modulation can be implemented in integrated circuit drivers suitable for high-volume, low-cost manufacturing.

Viscous and surface tension effects limit the volume modulation range obtainable by modulating the second delay to approximately 2:1. (Note that the volume modulation is continuous over this range.) To broaden the dynamic range, multiple (modulated) drops per spot can be used. Normally, this would result in a decrease in throughput because the spot generation rate would decrease for a fixed maximum droplet generation rate. However, if the length of the ink channels is adjusted to be L/N, where L is the length used for a single drop per spot and N is the number of drops per spot, the throughput will remain constant when using multiple drops per spot, because the resonant frequency is inversely proportional to ink channel length. Droplet volume is directly proportional to channel length when the entire channel length is driven. Thus, a printhead with ink channel lengths L would produce a drop with a maximum volume V at a maximum rate F, and a printhead with ink channel lengths $L/3$ would produce 3 drops per spot with a combined maximum volume V at a (spot) rate of F. The work presented here uses a maximum of two drops per spot.

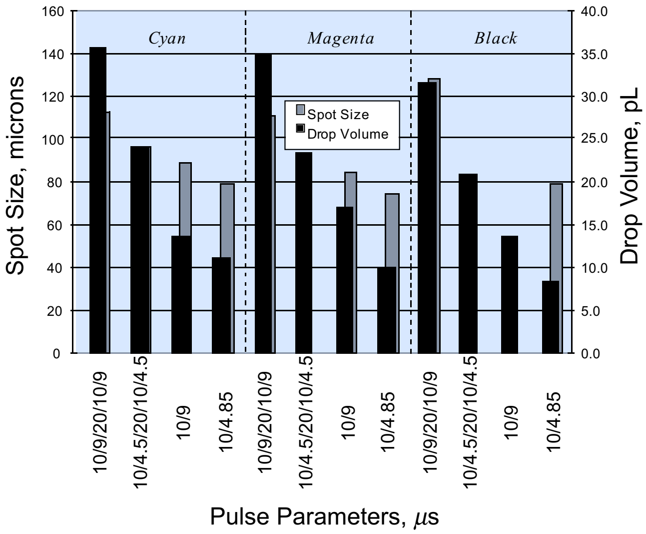

Figure 7. Droplet volume and spot size versus pulse parameters for three inks and three printheads at 3 kHz.

Experimental Results

Drop Volume Modulation. Using the printhead design and droplet volume modulation methods described above, drop volume modulation results as shown in Fig. 7 were obtained. The pulse parameters in Fig. 7 represent the four pulse widths when using two drops per spot (two pulses per spot) and the delay between the two pulses in the following order: width 1*p*, width 1*n*, delay, width 2*p*, width 2*n*, where 1 and 2 refer to the first and second bipolar pulses, and *p* and *n* refer to the positive and negative portions of the bipolar pulses, respectively. Where only two numbers are given, a single drop per spot was used. For each of the three ink/printhead combinations shown, the drop volume was continuously modulated between the largest two volumes and the smallest two volumes. Spot size data were obtained by printing onto coated paper with Compaq's solvent-based ink.

Spot Size Modulation. To demonstrate both the spot size modulation range and the real-time nature of the methods employed, an image was generated in which every fourth pixel of a 300-dpi image was a different gray level, each corresponding to a different drop volume/spot size. This image, which was printed right to left at a line rate of 3000 per second, is shown as the photomicrograph in Fig. 8.

Image Generation. To assess the impact of drop volume modulation on image quality, images were printed at both 300 and 600 dpi. Both monochrome and color images were generated. To construct a lookup table for drive waveform versus gray level, first solid areas were printed, both at 300 and at 600 dpi. Each solid area was printed with a different spot size. Different printheads were used for the 300- and 600-dpi cases in order to match properly spot size range with print density. Optical densities were then measured. To assign drop volume levels to values of a 256-level gray-scale image, the optical densities were converted to reflectances, the largest drop volume was assigned to level 0, and the paper (no drop) was assigned to level 255. The entire range of drop volumes producible by the printhead was assigned gray-scale levels by linearly interpolating the reflectances. Figure 9 illustrates a typical optical density and gray-scale level result. Pulse parameters are as described for Fig. 7. Note that there is a gap in the optical density curve between single and double pulse modes.

Because the gray-scale levels corresponding to the drop volumes produced do not cover the entire range of 255 levels, those levels that had no corresponding drop volume were created, using error diffusion halftoning. In each image, the highlight levels with no corresponding drop volumes were created by halftoning (error diffusion) with the smallest volume drop and no drop as the two levels. The shadow levels with no corresponding drop volumes were created by halftoning (error diffusion) with the two drops bounding the region. Although straightforward in concept, use of commercial image-processing software requires a tedious set of image splitting, mapping, halftoning, remapping, and recombining to accomplish this.

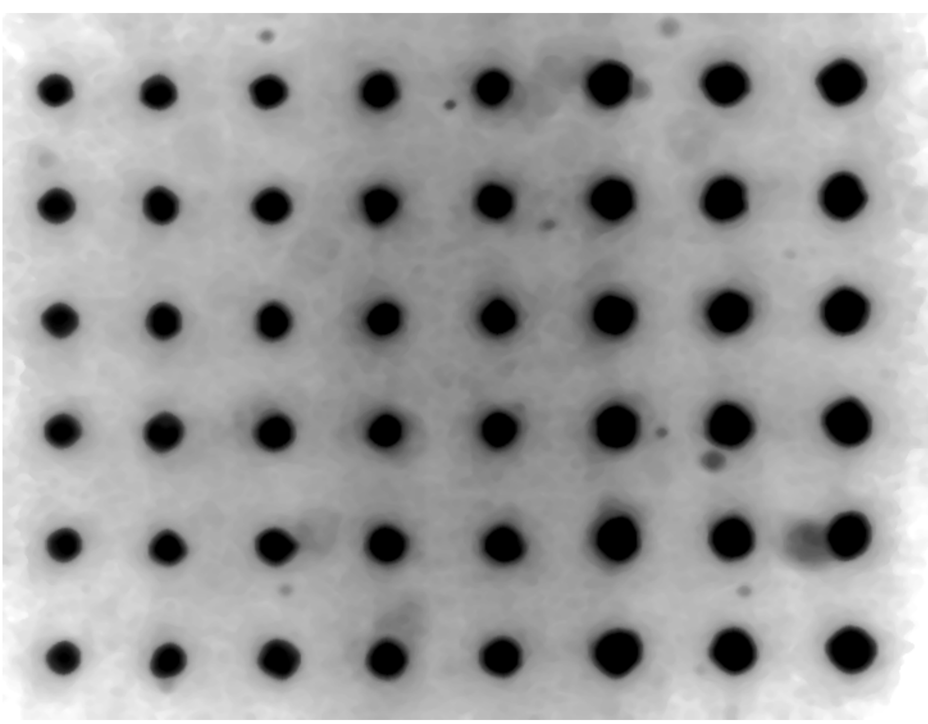

Figure 8. Photomicrograph of 4:1 real-time spot area modulation: 300 dpi with every fourth pixel printed; 3000 lines/second.

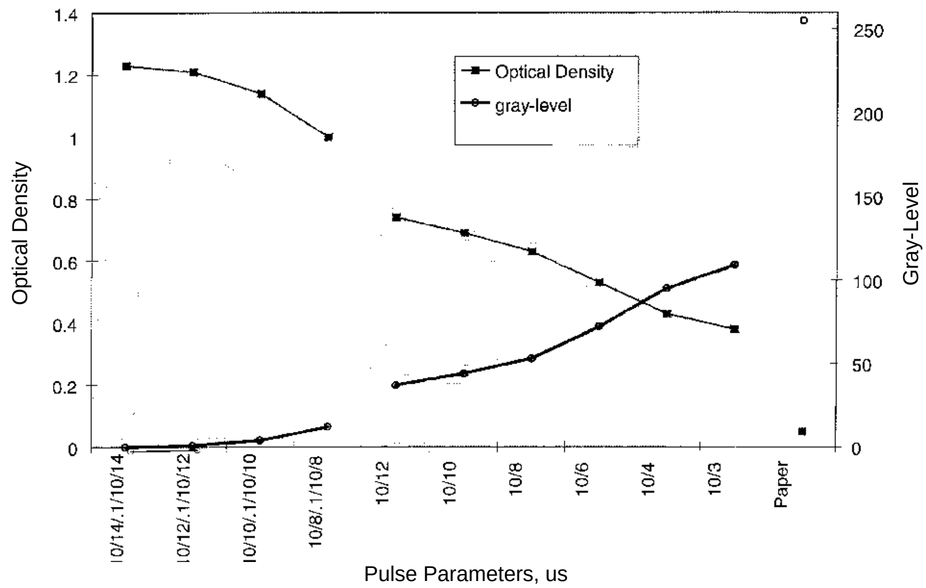

Figure 9. Optical density and 8-bit gray levels versus pulse parameters.

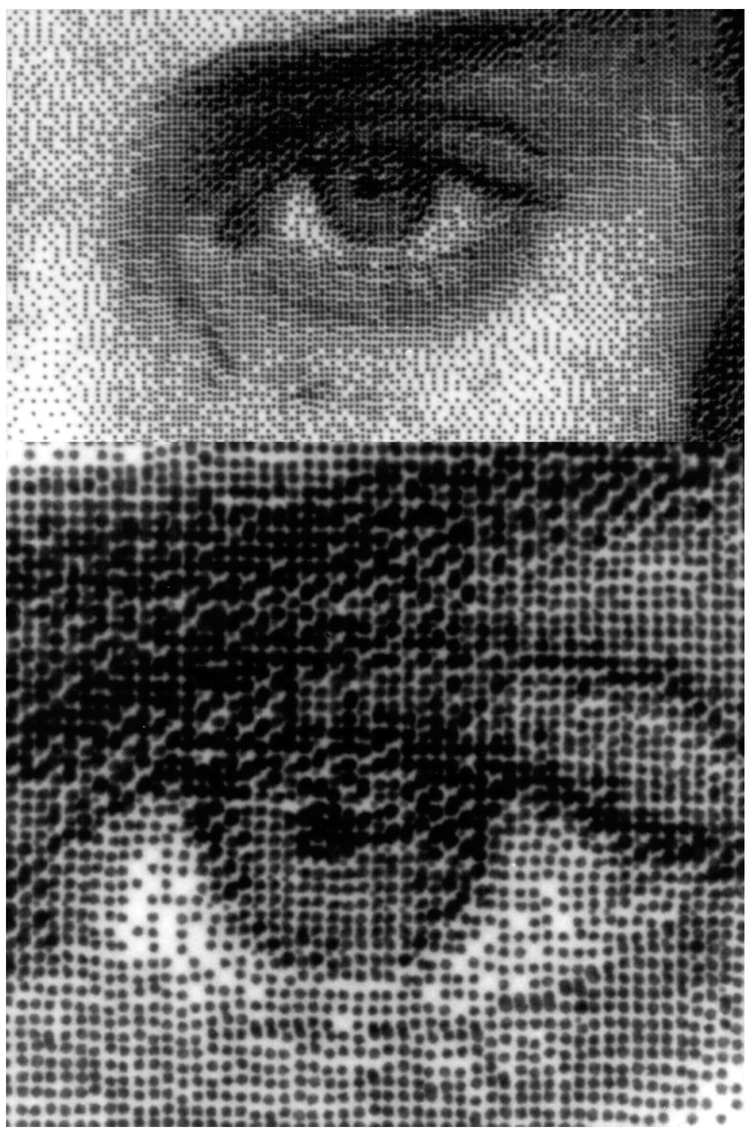

Figure 10. Photomicrograph of image printed using spot volume modulation.

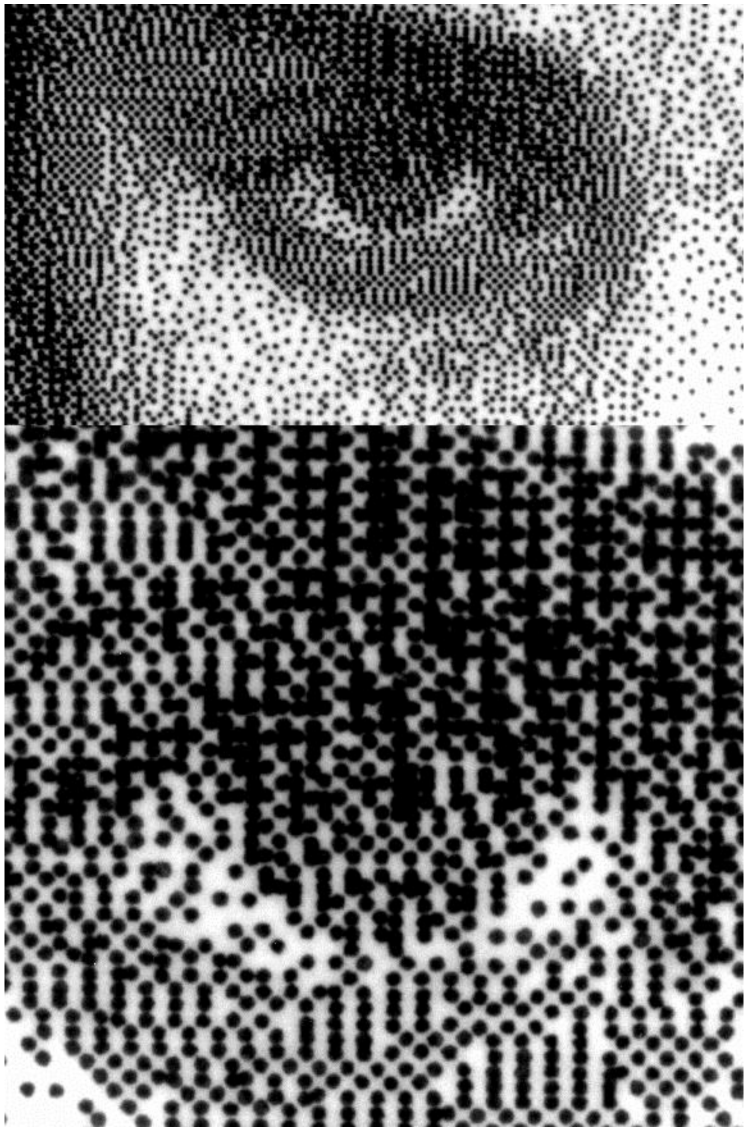

Figure 11. Photomicrograph of fixed spot printing using the same printhead and original image as was used in Fig. 10.

A photomicrograph of a monochrome image printed using the volume modulation method and image processing described above is shown in Fig. 10. For comparison, the same original 256-level gray-scale image was printed, using the same printhead with a fixed spot size and conventional error diffusion halftoning. A photomicrograph of the resulting image is shown in Fig. 11.

Conclusions

A method has been developed for dynamically modulating the drop volume created by an array piezoelectric drop-on-demand ink-jet printhead. This method has been used to increase significantly the quality of continuous-tone monochrome images printed at 300 and 600 dpi. A 4:1 range of volume modulation has been achieved to date, using a combination of waveform shape modulation and up to two pulses per pixel. The method can be extended to at least four pulses per pixel, which would result in an 8:1 volume modulation range. Use of this method for color images should produce images of photorealistic quality.

Acknowledgments. Carol Scalf, Jim Stortz, and Todd Podhaisky of Compaq Computer Corporation were instrumental in the development of the printhead, electronics, and software utilized for the work described in this study.

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