Xaar Greyscale Technology

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Abstract

Xaar technology can print at 360 dpi with 8 levels of grey; this capability is reaching the market in the form of the XaarJet XJ500S.

Xaar achieves greyscale printing by rapid ejection of multiple droplets, which merge to produce a single dot on the paper. The basic piezoelectric operation of the technology is explained, whereby shear mode deformation of shared walls causes acoustic waves in channels, resulting in ejection of droplets. The waveforms used to operate the printhead are explained.

The nozzle plate is made of polyimide; the nozzles are ablated, nine at a time, using an excimer laser and special optics. Great care is taken over cleanliness, in order to avoid nozzle blockages; integrated filters are provided to each of the four colour manifolds.

The printheads incorporates an RS232 interface for printhead configuration and a 4-bit bus for data communication, a microcontroller, EEPROM for configuration storage, voltage control according to actuator temperature, and special purpose drive chips.

The actuator and electronics are mounted on an aluminium chassis to provided good heat sinking, and special waveforms can be used on non-fired channels to maintain temperature uniformity.

Introduction

Xaar is developing piezoelectric drop on demand ink jet technology, and bringing it to market in the form of the XaarJet XJ500S and XJ1000S.

This paper describes the fundamentals of the shear mode shared wall actuator, and the acoustics of its operation. Xaar achieves greyscale printing by firing in rapid succession multiple droplets which merge to form dots of variable size.

The XaarJet XJ500S provides 500 jets at 180 dpi, and the XJ1000S interleaves two sets of 500 jets to print at 360 dpi. The printheads incorporate actuators, drive chips, electronics for waveform generation and data handling, and voltage control; the actuator and electronics are mounted on a chassis for good heat dissipation.

Actuator Fundamentals

The Xaar actuator is based on a piece of PZT with channels sawn to form ink channels. Figure 1 shows a cross-section through the channels.

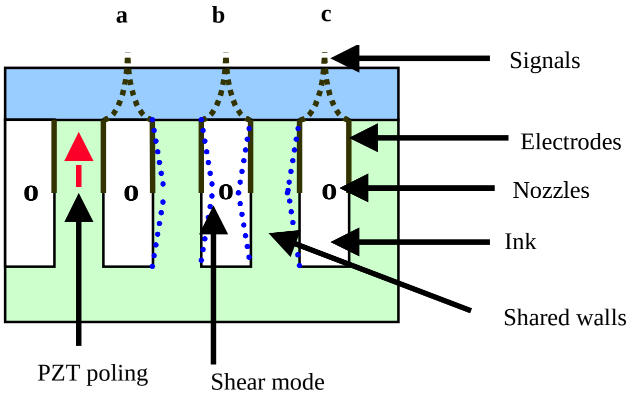

Figure 1. Actuator cross-section

A further piece of PZT, the cover component, provides a roof to the channels over an active length; Figure 2 shows a longitudinal section through the actuator:

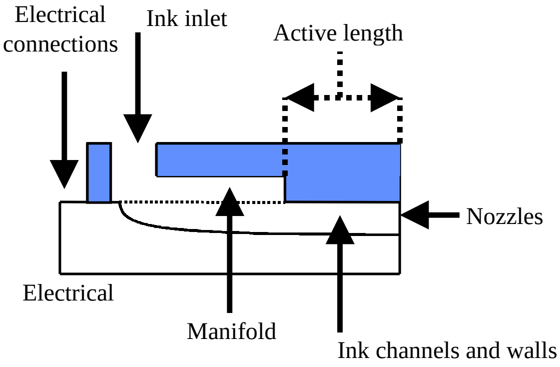

Figure 2. Actuator longitudinal section

Electrodes cover the top halves of the channels; these run out of the channels to an electrical interconnect region at the rear of the channelled component. Signals are applied as indicated schematically in Figure 1.

Ink is fed into the channels, at a pressure slightly below atmospheric, via a hole in the cover; this leads to a manifold formed by an undercut in the cover. The active length of the channels is defined at the rear by the undercut, and at the front by a nozzle plate.

The actuator operates as follows:

The channels are fired in three cycles as indicated by the signals a, b and c in Figure 1. At a given moment, when it is the turn of the b cycle channels to fire, waveforms are applied to the electrodes as shown in Figure 3:

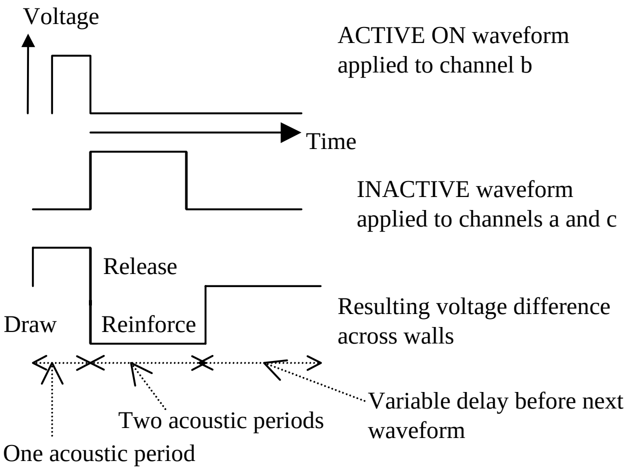

Figure 3. Drive waveforms

The voltage across the walls is the difference between the ACTIVE ON signal applied to the b channel and the INACTIVE signal applied to the neighbours.

The top halves of the walls, where the electrodes produce field in the PZT perpendicular to the poling direction, move in shear; the bottom halves are forced to follow, producing a chevron shape. As the walls are tall, the shear mode of actuation produces a large volume displacement. The volume in the narrow channels is small, so a substantial change in pressure is created throughout the active length of the b channel.

The initial rise in the voltage difference causes the walls bounding the b channel to move outwards (the draw), resulting in a negative pressure in the channel. Compressional waves move into the channel from the manifold and from the nozzle, restoring to atmospheric the pressure at each end of the channel. The waves cross, creating a region of positive pressure in the centre; this grows until, after one acoustic period (the time taken for a wave to travel the active length of the channel) the entire active channel is under positive pressure.

At this point the reversal of the voltage across the wall causes the walls to move inwards (release and reinforce). This creates further positive pressure, and starts the process of droplet ejection. Now rarefaction waves travel into the channel from each end, reducing the pressure back towards atmospheric. These cross in the middle, creating a growing region of negative pressure. Droplet ejection continues for one acoustic period, with the backward-travelling wave providing the ink flow through the nozzle. Then, despite the fact that the voltage across the walls does not alter at that moment, the arrival at the nozzle of the forward-travelling wave causes an abrupt drop in pressure there; this brings to an end the active ejection of ink. The negative pressure at the nozzle, combined with the momentum of the ink already ejected, causes the droplet ligament to neck. In practice the droplet finally breaks off some time later, irrespective of the details of the subsequent waveform.

After a further acoustic period, the voltage difference is returned to zero. This tends to cancel the positive pressure which, by then, has been created by further waves in the channel. The waveforms end with a settling period to allow all waves to die away; this can be as long as three acoustic periods, or as short as half a period if printing speed is of the essence.

The result of the above sequence is the ejection of a single droplet from the b channels. If a droplet is not required from a particular b channel, it receives an ACTIVE OFF signal which is similar to the INACTIVE signal; there is then no voltage difference across the wall, so it does not move, no pressure is created in the channel and no droplet is ejected.

In binary printing, the sequence given above is applied to the a, b and c channels in succession to complete the printing of a single row of pixels in the image. The reason for the three-cycle firing scheme is that when positive pressure is created in an active channel to fire a droplet, negative pressure exists in the neighbouring channels, so they cannot fire at the same time. During the draw phase of an active channel, when negative pressure is created there, the neighbours experience positive pressure; however, this is insufficient to fire an unwanted droplet, because the reinforcement described above has not taken place. In order to compensate for the delay between the cycles, the nozzles are staggered by a third of a pixel pitch.

Greyscale Technology

Xaar technology achieves high print quality by means of medium resolution combined with greyscale, rather than by very high resolution binary printing. Print at 360 dpi with 16 levels of grey is equivalent for many purposes to 1440 dpi binary print. This level of print quality is achieved, however, without using large number of nozzles or multiple passes, as required by the very high resolution strategy.

Xaar technology achieves greyscale printing by firing multiple droplets; these merge on the substrate to form a dot of variable size. The waveforms described above are repeated rapidly, producing (currently) up to seven droplets, which together constitute the required drop of variable size. A typical sequence of waveforms is shown in Figure 4.

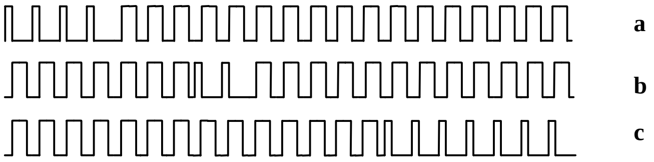

Figure 4. Greyscale waveforms

In the case illustrated here, an a channel fires four droplets, then a b channel two droplets and finally a c channel seven droplets during the printing of a single row of pixels. Successive droplets are ejected from a given channel so rapidly that they merge on the nozzle plate, in flight or on the paper to produce a single dot.

The individual droplets employed in greyscale printing need to be very small. This is achieved by using a shorter active length and a smaller nozzle. Because the acoustic period corresponding to a short active length is very small, the pixel frequency achieved is not much lower in greyscale printing than it is in binary printing. For example, with a 1 mm active length, the acoustic period is typically 2.2 µs, so if the settling period is half an acoustic period, seven droplets can be produced in each of the three cycles at a pixel frequency of 6.2 kHz.

In greyscale printing, the PZT is exercised at a very high frequency. Any hysteresis loss in the PZT produces heat; much of this is carried away with the ejected droplets, but the remainder raises the temperature in the channels. Channels which are working hard will tend to become hotter than those which are printing less. Since the temperature of the ink at the nozzles is important in determining (through the ink viscosity) the volume and velocity of the droplets ejected, there is a danger that dots will be printed whose size and position depend on the data in the image.

The temperature is maintained uniform across the printhead, irrespective of the image being printed, by means of special waveforms. When a channel is active, but is not being asked to fire a droplet, it receives an ACTIVE OFF waveform which is the same as the INACTIVE waveform being applied to the neighbouring channels, but shifted a little in time. The result is that the voltage difference across the walls consists of a brief positive pulse, followed two acoustic periods later by a negative pulse. This signal exercises the PZT somewhat, but does not lead to the ejection of a droplet. The heat dissipated corresponds to that portion of the heat generated during the firing of a droplet which is *not* carried away with the droplet. Thus the temperature rise in a channel which is not firing a droplet is the same as it is when the channel is firing.

This scheme ensures that the temperature distribution in a printhead is independent of the image it is printing. The ACTIVE OFF waveform is also potentially useful for warming a printhead to its operational temperature prior to printing.

Most greyscale images have 256 levels of grey; since Xaar's approach to greyscale accommodates eight levels at present, and perhaps 16 in the future, the data has to be reduced. Xaar has an algorithm for applying patterns to the data to produce choices of greyscale level in each pixel in such a way as to avoid visible sharp transitions, aliasing, Moiré fringes and other undesirable artefacts.

XaarJet Greyscale Printheads

XaarJet manufactures the XJ500S printhead, which embodies the principles outlined above. The overall configuration is shown in Figure 5.

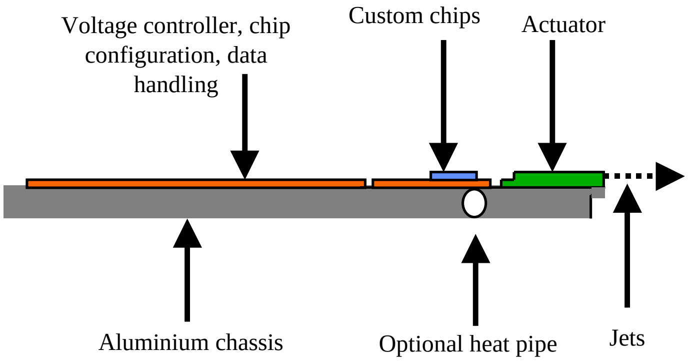

Figure 5. XaarJet XJ500S

The printhead consists of an aluminium chassis; the PZT actuator; custom drive chips on an alumina substrate, and a further substrate housing other electronics; ink filters and a cover (not shown).

The actuator has 500 channels, at 180 dpi pitch. The manifold is divided into four sections, each feeding 125 nozzles. This allows four different colours, typically cyan, magenta, yellow and black, to be used for colour printing. Even for monochrome printing, the division is necessary to permit the head to be oriented with the row of nozzles vertical, without excessive pressure differences between the extreme nozzles. Each section of the manifold is equipped with a filter based on a stainless steel mesh achieving 8 µm absolute filtration.

The channel active length and nozzle are sized to produce droplets appropriate for greyscale printing at 360 dpi. As the channels are at 180 dpi pitch, it is necessary to use two passes to print correctly at 360 dpi. The XJ1000S, currently under development, will combine two 500-channel actuators in a single unit which prints at 360 dpi in one pass.

The chassis acts as a heat sink for the printhead. The minority of the heat dissipated in the actuator which is not carried out with the ink is conducted to the chassis. The temperature rise in the channels is only a few degrees above the chassis temperature. There is also considerable heat generated in the drive chips, and in the voltage controller circuitry. Most of this heat is conducted to the chassis, which is optionally fitted with a heat pipe under the chips. The chassis and heat pipe act as an overall heat sink, but they also ensure that all parts of the actuator are at the same temperature, whatever image is being printed.

The drive chips are a custom ASIC developed jointly with NEC. Each chip generates the drive waveforms described earlier, and distributes them to 64 channels according to the image data. The chips handle the three-cycle firing currently used, but they can also accommodate other possible schemes.

Figure 6 shows the output stage of a chip.

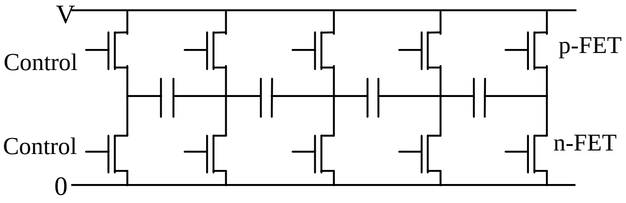

Figure 6. Output stage of drive chip

The capacitors describe the load presented by each wall, and the nodes where the capacitors are connected to the FETs represent the electrodes on the walls. The chip controls the FETs in such a way as to connect each electrode either to ground or to the power rail. The waveforms for each droplet are specified in terms of 32 samples, each lasting a time adjustable down to a minimum of 83 ns. During each sample the relevant electrode is at ground or at rail, with the transition time between levels determined by the output impedance of the FETs and the capacitance of the walls; a typical rise time in greyscale printheads is 400 ns, which is comparable with the resonant response time of the walls. The ACTIVE ON, ACTIVE OFF and INACTIVE waveforms can be specified independently for each one of up to 15 droplets per drop.

The electronics on the substrate at the rear of the printhead is shown in Figure 7.

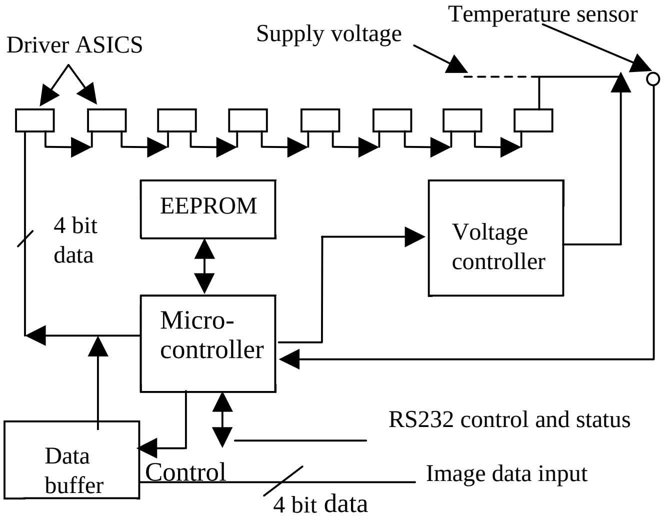

Figure 7. Printhead block diagram

This circuitry has two main functions: to store the configuration information which defines the firing waveforms to be generated by the ASICs, and to provide a variable power supply to them which compensates for the variation of ink viscosity with temperature.

Communication with the printhead is via a 37 way D connector incorporating an RS232 interface and a 4-bit data bus. Configuration information is initially loaded via RS232 and stored in an EEPROM. The micro-controller copies the waveform information from the EEPROM into the ASICs at power-up or on demand. Incoming 4-bit data is directed via a buffer to the chips when printing.

As well as waveform information, the configuration data contains: serial number, number of grey levels, number of cycles in the firing scheme and a lookup table for voltage control.

During printing, incoming image data is fed to the first chip, and cascades along the printhead to the eighth one. While a row of pixels is printing, data for the next row is loaded into the chips.

If only one bit of the bus is used, the chips support binary printing, or multipulse binary (in which dots, of a size globally adjustable for the medium being used, are printed according to binary data).

Also on the rear substrate is a voltage controller, which adjusts the power rail to the chips according to the actuator temperature measured by a resistance thermometer and the look-up table stored in EEPROM. Alternatively, the temperature can be reported to an external controller via the RS232; in this case, the on-board voltage controller produces a fixed fraction of the incoming voltage. In either case, the aim is to operate the printhead at a voltage which is appropriate to the viscosity of the ink in the channels, so as to produce a consistent droplet velocity as the printhead warms up or ambient temperature varies. The printhead is always within the operating window between too high a voltage (which causes the nozzles to ingest air) and too low (leading to jet misidirection).

A possibility for the future is to build into the microcontroller a self-test image.

Manufacturing Processes

The manufacture of XaarJet printheads involves various processes which are critical to quality and yield. The first is PZT machining: it is not possible to use parallel processes, but the channels are sawn serially in a short time using a semiconductor industry dicing saw. The advantage of using a numerically controlled process is that alterations can be programmed easily. It is also possible to make long arrays of channels.

Special cooling arrangements are needed to prevent the PZT depoling under local heating and stress. Care is taken to minimise grain pull-out, as this leads to reduction in the effective piezoelectric thickness of the walls.

The walls are ‘prepassivated’ with silicon nitride. The purpose of this is to cover the non-active parts of the walls with a micron layer of low dielectric material, prior to application of the electrodes. (The parts of the walls intended to be active are masked from the prepassivation.) The silicon nitride is applied by electron cyclotron resonance chemical vapour deposition, using a plasma of silane, nitrogen and argon. The cyclotron radiation excites the plasma in such a way as to produce deposition of silicon nitride with very low inclusion of hydrogen, without producing excessive heating – the Curie temperature of the PZT must not be exceeded.

The rationale for prepassivation is as follows: because PZT has an extremely high dielectric constant, most of the voltage difference across the walls appears on the silicon nitride layer, and very little on the PZT. As a result, the stray capacitance of the non-active parts of the wall is minimised, which reduces currents and makes it easier for the drive chips to achieve a fast rise-time. In addition, the open-topped walls in the non-active part of the channels do not move much; open walls are not very stiff, and without prepassivation they would cause unwanted acoustic waves in the manifold region of the printhead.

The electrodes are applied by a line of sight vacuum deposition process. A crucible of molten aluminium is heated by a scanned electron beam, and emits aluminium atoms in a direction broadly towards the actuators. The channelled component is tilted, first one way and then the other, so that each wall shadows its neighbour and limits the depth of plating to the top half of the channel. Argon ion bombardment is used to clean the surface before the aluminium is applied, and is continued for the first stage of metallisation to ensure good adhesion by driving the aluminium atoms into the PZT structure.

Aluminium is chosen, despite its high reactivity, because it forms a coating with low residual stresses. A more corrosion-resistant material such as nickel, because of its high melting point and elastic modulus, tends to develop stresses as it cools following deposition and subsequently spalls. Gold is malleable, but expensive to use in a process which wastes much of the material. Another reason for the choice of aluminium is that it is amenable to wire bonding to the chips.

The metallisation needs to be patterned to separate the electrodes and to produce wire bond pads at the chip output pitch (125 μm) rather than the channel pitch (141μm). This is done photolithographically: prior to metallisation, a resist is applied everywhere, and cured with UV light and a mask in the places where aluminium will not be required; the uncured resist is washed off and then metallisation is carried out. Now a liftoff removes the cured resist and aluminium where plating is not wanted.

After metallisation/patterning, silicon nitride passivation is applied, except in the wire bond areas. This time the silicon nitride is intended as an ionic and electron barrier, to prevent corrosion of the electrodes by the ink.

Next the cover is glued to the channelled component. The necessary thin rigid bond is achieved by the use of a press; it is essential that both PZT components and one of the platens of the press are highly flat, and that the other platen has the correct degree of compliance. The adhesive has to be extremely well mixed, because inhomogeneities on the micron scale of the bond line thickness lead to variations in the stiffness of the walls.

All the processes so far are carried out at wafer scale, so six printheads are made at once. At this stage they are diced apart, guaranteeing the coplanarity of the two components at the nozzle plate face. The polyimide nozzle plates are attached with a thin layer of adhesive.

The actuators are assembled, with the two electronics substrates, onto the aluminium chassis. The glue used is sufficiently thick and flexible to avoid either bowing of the assembly or excessive stress in the glue.

The chip outputs are connected to the pads on the rear of the actuator by aluminium wedge wire bonding. This is suitable for the high interconnect density, and uses purely ultrasonic excitation – gold ball bonding is marginal on interconnect density and requires a degree of heating which would threaten the PZT Curie temperature. The wire bonds are encapsulated with a gel which keeps any ink away, prevents the wires touching each other and does not tend to lift the wire bonds under thermal cycling. Mechanical, environmental and EMC protection are achieved by a moulded cover which goes over the actuator, electronics and filters.

Ablation of the nozzles is performed with an excimer laser. Xaar uses in situ ablation because otherwise registration of nozzle positions to the corresponding channels is difficult, given the width and flexible nature of the nozzle plate. The beams of light therefore have to be divergent to produce the desired nozzle shape. This is achieved by imaging a circular hole in a mask through a high numerical aperture objective onto the front surface of the nozzle plate. The resulting ink exit face is of high quality, while the less critical ink entry is ablated by out-of-focus (but collimated) light. It is now possible to ablate nine nozzles at a time by using a mask with multiple holes.

The printhead is flushed through with solvent, while the walls are exercised at the same time, to clean out manufacturing debris and establish the presence of all 500 lines. The entire manufacture takes place in a class 10000 clean room, with critical process in class 100 laminar flow cabinets, so yield is good. Finally, the printhead is soak tested with ink prior to dispatch.

Biographies

Dr. H. J. Manning, an applied physicist with leanings to mechanical engineering, has expertise in heat transfer, fluid flow and instrumentation. He has worked on domestic heating systems and in the oil industry and has ten years experience in ink jet printing. He has run projects on continuous ink jet and drop on demand ink jet. He is currently Systems Manager at Xaar Technology Ltd.

Mr. R. A. Harvey is a mechanical engineer with a track record of work in micro-engineering and systems design. He has developed a wide range of products in industrial and scientific instrumentation, and had been involved in the development of Xaar technology for over ten years. He is currently Engineering Manager at Xaar Technology Ltd.