Three-fold Increase in Inkjet Speed of Piezoelectric Shared Wall Technology Exploiting Single Cycle Operation

Paul Drury, Julian Bane, Alison Morris, Mario Massucci and Tri Tuladhar; Xaar plc, Cambridge, England

Abstract

A combination of novel piezoelectric inkjet print head technologies such as greyscale, shared wall and genuine through-flow have led to the development of inkjet print heads able to deliver the quality and reliability demanded by modern single-pass printing applications. While shared wall technology can provide benefits such as acoustic firing and reduced drive voltage, there are limitations in the final achievable firing frequency, dictated by a 3-cycle firing pattern (active-idle-idle). As a result the print speed is restricted.

Recent advances in the exploitation of the base shared wall technology have allowed the development of single cycle nozzle operation (always active) for shared wall devices. This has yielded approximately a three-fold increase in firing frequency and hence the three-fold increase in print speed from a print head of similar footprint. Such dramatic improvement has been possible by deeper understanding of the events involved in the complete drop ejection cycle combined with clever rearrangement and overlapping of the events for arrays of nozzles working in synchronization.

Three implementations of a single cycle operation have been explored, some which impose imaging limitations and others which use technically complex solutions but imaging capabilities are unhindered. Commercialization of these technology variants is currently underway with some already deployed in end user production environments.

Introduction

Digital printing technologies have displaced many analogue imaging processes and some have enabled new markets. Increasingly, digital inkjet is used to replace certain deposition and printing technologies in the fabrication of devices, e.g. manufacture of 3D components, displays, solar panels and electronic circuits. The emerging digital technologies are favoured for their increased agility and efficiency when compared to many of the incumbent analogue printing processes, but often the raw production throughput of the digital process is reduced. There are many opportunities for a digital printing technology which is capable of combining increased production throughput with the other key demands of industrial inkjet applications.

The shared wall piezoelectric inkjet actuator has been chosen by many print head manufacturers and is widely employed in printing systems addressing a diversity of imaging and deposition applications. The physical structure of this type of device is shown in Figure 1 and comprises a linear array of walls formed in a piezoelectric material with electrodes connected to each channel. A field across each wall causes a deflection in the shear mode and pressure change in the fluid. The simplicity of this structure, efficient use of piezoelectric material, small footprint and careful process design enables low fabrication costs and high native resolution. With many of the processes adapted from semi-conductor, MEMS and optical industries capital equipment is readily accessible. Today implementations of the shared wall actuator operate by deflecting the wall pair which neighbours the channel from which droplet ejection is required. The displacement of each wall generates a pressure of ½P so collectively a pressure pulse of magnitude P, sufficient to enable droplet ejection. As a consequence opposing pressures, resulting from the same oscillation but 180 degrees phase shifted, of magnitude ½P result in neighbouring channels. If these are not well managed they can cause accidental droplet ejection or air ingestion. For example, were alternate channels to be operated a common neighbour would receive pressure contributions of ½P from each, so that ejection would occur.

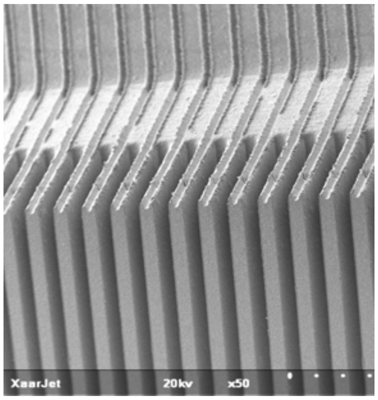

Figure 1. *Micrograph of a shared wall array*

A common approach to solve these problems is the operation of the channels in a cyclic manner such that the pressure in neigbouring channels is prevented from exceeding ½P and is allowed to decay while channels assigned to other cycles are active. Unfortunately this approach allows only one third of the channels to function, i.e. while their phase is active, so the resulting print frequency is likewise reduced. Devices operating in this 3-cycle mode yield linear print speeds near to 0.5 ms^{-1}, which at an effective resolution of 1080 dpi (360 npi, 8 grey levels) in a single pass, has proven satisfactory in many a wide range of applications. However, modern printing systems (e.g. those with high speed scanning carriages, and web or sheet fed single pass transports) demand additional productivity such that increased deposition rates are sought.

A value metric employed to rank the relative performance of print heads is that which calculates the volume of ink delivered per unit cost of the print system, for example pl.kHz/$. Some developers, accepting the doubling of print head cost, have shown how productivity of the system can be increased by stacking a second array of print heads in the print direction. Others have employed print heads configured to eject at a higher frequency from nozzles communicating with alternate channels, but accepting this productivity is hampered by the reduction in active nozzles. In both examples, while productivity is increased, the value metric is unlikely to be improved significantly.

Desirable is a shared wall actuator which can be configured to eject concurrently from a nozzle in every channel in the array to increase print head productivity and the value metric.

Acoustic Operation

The active ink channel, formed by the shared wall structure, communicates with a manifold providing a source of fluid to replenish that ejected from the nozzle. It is desirable to have a manifold of adequate cross-section such that the pressure drop in the fluid supply is small. This change in cross-section, between the active channel and the fluid manifold, causes partial reflection of pressure waves, providing an opportunity to cause droplet ejection by the accumulation of pressure pulses from a multiple of operations of the actuating element.

Acoustic operation is initiated by activation of walls either side of the nominated active channel. If the walls are deflected such that the volume of the chamber is increased the result is a reduction in fluid pressure, of magnitude P (arbitrary units). This negative pressure is reflected at the manifold and a positive pressure wave (+P) propagates away from the manifold toward the inkjet nozzle. After a period and when the pressure wave is close to the nozzle the channel walls are returned to their starting position. The change in channel volume results in an increase of pressure of similar magnitude as the reflected wave, so that the total pressure at the nozzle at this instant is approximately 2P. A further pressure increase, to a total magnitude of approximately 3P, can be achieved if at the same time the wall pair makes a second movement further reducing the channel volume. Of course if a pressure of magnitude P is required to initiate droplet ejection the device can be operated with a substantial reduction of the appled voltages.

Figure 2 shows the fluid pressure profile measured at the nozzle in an arbitrary channel (channel 1) in the shared wall array. Label A identifies the pressure peak, of magnitude ~3P, which is adequate to eject the fluid from the nozzle. The subsequent low pressure pulse initiates thinning of the sub-drop ligature in preparation for subsequent sub-drops or break-off of the last drop if the drop has developed to the desired volume. Figure 2 shows the natural decay of the pressure wave however in operation these pressures are controlled by the introduction of further pressure pulses which are timed to enable active cancellation.

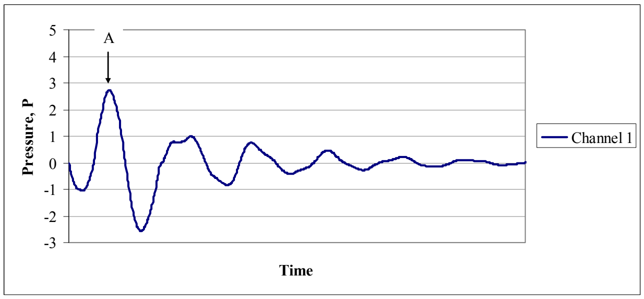

Figure 2. *Fluid pressure profile measured at the nozzle showing the result of longitudinal acoustic operation.*

Actuators configured in this manner are able to operate at high frequencies since the time of flight of the acoustic wave along the length of the channel is short. In addition the flow of ink required for effective nozzle replenishment is free from impediment as a result of the proximity of the manifold and unrestricted channel cross-section. These short cycle and recovery times enables ejection at frequencies in excess of 200 kHz (6pl drop) without risk of fluid starvation.

The resulting maximum usable pixel frequency, with dead time between pixels, is close to 24 kHz but the 3-cycle mode erodes this frequency by a factor of 3 (e.g. a theoretical maximum of 8 kHz).

Single Cycle Operation

It is possible to generate pressure in the channels other than by movement of wall pairs as in the 3-cycle mode so that opportunity to increase print head productivity exists [2] [4]. Consider the wall array shown in figure 3 in which the centre wall is displaced. Oscillation of this wall stimulates longitudinal acoustic pressure waves in the fluid within each of the neighbouring channels. These waves and the sub-drops ejected from neighbouring channels are subject to the phase shift described previously and which (at 200 kHz sub-drop frequency) results in a ~2.5µS delay between sub-drops in each phase. Usefully each print pixel, formed by a drop made up of a number of sub-drops, is addressed within a single cycle of operation.

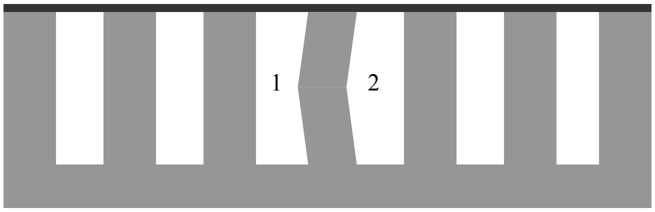

Figure 3. *Cross section showing single wall actuation.*

Figure 4 represents the pressure waves in these channels and the legends A and B show the pressure peaks corresponding with sub-drop ejection from nozzles communicating with channels 1 and 2 respectively.

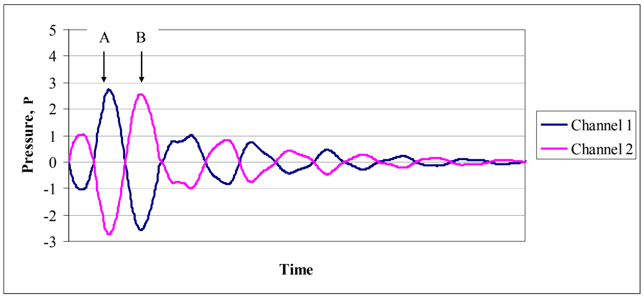

Figure 4*. Fluid pressure profile measured at the nozzle showing the phase shifted longitudinal acoustic operation in adjacent channels.*

In a first form of single cycle operation the channel pairs to print are mapped onto the input image (i.e. the location of selected neighbour channels pairs is allowed to float) using the full addressability of the channel array. In a multi-pulse binary mode these pressure peaks would repeat producing multiple sub-drops until the main drop volume, require to fill the pixel, is satisfied. Note that drops must be ejected in pairs hence the image resolution, in the direction for the nozzle array, is low.

It is possible to eject drops from all nozzles, for example by moving every alternate wall, so that the increase in productivity can be realized across the full array of nozzles. This is shown in the stroboscopic image shown in figure 5.

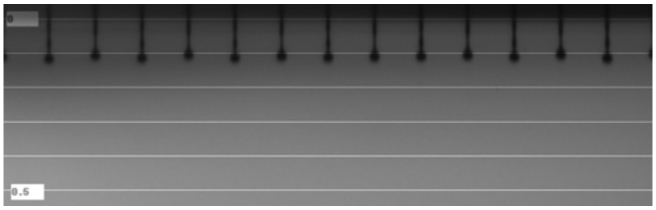

Figure 5. *Single cycle, 2-phase operation of 42 pl drops (7 drops each at 6pl) emerging from a 180 dpi nozzle and shared wall array.*

To a first order this type of single cycle operation results in no pressure being transmitted to those channels which neighbour the active pair since those dividing walls remain stationary. As a result it is possible to use drive voltages which generate pressures higher than that necessary to eject drops without risk of accidental drop ejection or ingestion of air. Higher pressures produce drops which have larger volumes and higher velocities. It has been possible to increase drop volume and substrate coverage so that further increases in linear speed have been demonstrated in excess of 2.5 m/s. The increase in drop velocity to more than 10 m/s aids the control of drop flight and landing accuracy. This represents a first mode of fast binary operation, referred to in this paper as Type 1. Current performance of this technology, apparent resolution and linear speed, is illustrated in figure 6.

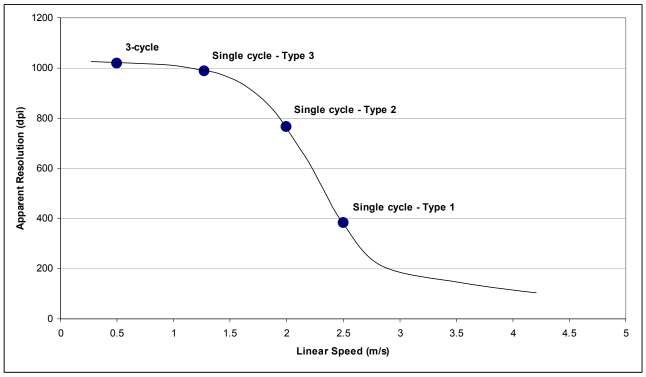

Figure 6. *Print performance shown as an apparent resolution against linear speed in a single pass. Note print heads having 360 npi capable of full coverage in a single pass at the stated speeds.*

The Type 2 configuration is a greyscale variant of Type 1. In both if channel 1 ejects n sub-drops then channel 2 can only eject n-1, n or n+1 sub-drops which offers little flexibility in respect of greyscale functionality. Instead greyscale levels are applied to the channel pairs each ejecting a maximum of n sub-drops. Figure 6 shows how the Type 2 configuration can deliver a higher image quality, as a result of the greyscale functionality. Here the linear speed is shown lower than that of Type 1 as a result of the other imaging constraints, namely the selection of a different print strategy requiring a small sub-drop which prevents increases in drop volume being fully exploited.

A further refinement has been developed in which previous limitations have been overcome. The Type 3 embodiment employs a new design in which the wall displacements, and hence channel pressures, are more freely addressed. This has enabled a channel operated in a greyscale, single cycle mode to have neighbours which can be operated in a similar manner without substantial interaction between. With this technology we have shown it possible to configure a shared wall device, delivering an apparent resolution of ~1000 dpi, to operate at a linear speed three times faster than the original and without deterioration of the resulting image quality.

The single cycle methods described deliver a print productivity which is increased by a factor of 3 compared to the 3-cycle schemes described earlier in this paper. Print heads carrying the new shared wall actuator operate at triple the frequency, delivering the same ink volume per drop and in the same print head package. Consequently the value metric (pl.kHz/$) is more attractive against the original 3-cycle configuration, designs which ultilise only alternate nozzles and some other arrangement stacking multiple heads.

Imaging for Applications

There are several embodiments of the shared wall actuator and print system which can be operated in the single cycle mode described, or in modes which represent simple variants. The operation of a single wall results in drop pairs being deposited in the substrate, this larger volume reduces the resolution in the direction of the nozzle array. Of course the resolution in the print direction can be varied, but for purposes of this paper we will consider this to be fixed, for example at 360 dpi. The resulting resolution of the printed image can be usefully expressed as an apparent resolution (AR) taking into account the scale of the pixel grid and the number of grey levels used to define the pixel tones [1]. Where a rectangular pixel grid is defined the pixel resolution is taken to be the average of the values in both axes, so:

$$\text{AR} = \text{Pixel Resolution} \times (\text{No. grey levels})^{1/2}$$

Most relevant to this paper is the Single cycle Type 3 device, which signifies the capability as an extension of similar devices configured to operate in the conventional 3-cycle manner. This Type 3 device can yield a 3 fold increase in linear speed while maintaining an apparent resolution of circa 1000 dpi. This capability will accelerate the acceptance of these technologies in applications such as labeling, high resolution marking and digital adoption of flexography.

Other applications, which can be satisfied by lower resolutions, have adopted devices having a performance shown by the Single cycle Type 1 label in figure 6. Coding applications requiring a binary image for the construction of barcodes or human readable text have previously adopted such shared wall technologies.

Fluid Choice

The increased print frequency and drop velocity made possible by this single cycle actuator technology imposes certain requirements on fluid selection; or preferably it demands that fluids are uniquely formulated for the specific printing application.

Droplet ejection characteristics are influenced; in the channel by the reaction of the fluid to acoustic stimulation; in the nozzle by the fluid being subjected to high shear stresses and in flight by visco-elastic and surface tension properties [3]. In all cases the demands imposed by single cycle operation are more severe. Also the fluid, the materials it comprises, the preparation of constituents and the manner in which these are blended into the fluid formulation further influence the ejection performance.

Reliable jetting at such frequencies is improved with fluids having a short relaxation time, i.e. lower than the jetting interval, so the fluid is fully relaxed and the stored energy dissipated before the next firing.

Droplet formation can be compromised with an increase in drop velocity or firing frequency. Satellite drops (resulting from poor sub-drop merging) and volumes of fine mist (by the break-up of the drop ligatures) can be more pronounced. It is the elastic component of the fluid that becomes more important and it is necessary to satisfy a certain elasticity at the print frequency for reliable satellite free drops.

Effective fluid selection or development requires a detailed understanding of the relationship between the ejection systems and the rheology of the fluid. Also, that key parameters can be easily measured in a representative manner or reliably interpreted from measurement data, and that the print system can be suitably configured.

The same fluid measurement techniques can play an important role in the ongoing quality monitoring of the printing system. Inks are easily screened for batch variation, signs of wear or degradation in use, contamination or premature ageing. It is possible to use such technologies to contribute the quality and reliability of modern inkjet printing systems.

This knowledge is used to develop new classes of fluids, including graphic inks, which have extended the performance of inkjet processes. In addition new classes of printable fluids are formulated which, coupled with advanced piezoelectric actuator technologies, are able to deposit materials in the manner demanded by emerging applications. Trends in fluid deposition (inkjet) mark the onset of a new class of additive fabrication processes which will employ the shared wall technology well into the next decade.

Role of the Peripheral Systems

Fundamental to acceptance of high speed single pass digital printing is the print reliability. It is the single cycle actuator which is capable of ejecting the fluid at the high rates demanded in future applications and that device must control precisely the pressure impulses in the fluid, the conversion of these into droplets in flight and the rapid recovery of parameters such that subsequent drops may be ejected without error.

However, high confidence in print performance and reliability require close control of thermal factors, nozzle meniscus pressures, and entrainment of bubbles, dissolved gasses, dirt and debris It is the peripheral systems that are configured to aid management of these in high speed single cycle operation. It is preferred to do much of this management in one system, rather than add to the complexity of the overall system, and the ink supply provides a number of opportunities.

Fundamentally the ink system supplies fluid to the print head to be ejected from the actuator nozzle array. This fluid is held in a remote reservoir under a vacuum which acts to remove excess dissolved gases. A first conduit is provided which allows the fluid to communicate with the print head, the inlet manifold, to pass through the pressure chamber before returning through an outlet manifold and back through a second conduit to the remote reservoir. In the first conduit a pump is provided to raise the pressure of the ink such that the fluidic impedance to flow is overcome. The fluid passes through a filter, removing particulate debris; and a heater which is controlled such that the fluid arriving at the nozzle is closely controlled. Pressure sensors at the fluid inlet and outlet to the print head monitor the pressure differential from which the fluid recirculation rate is derived and controlled. Also the sensor outputs are used to control the nozzle meniscus pressure. Having left the pressure channel the fluid starts on its recirculation path. Between the outlet manifold which communicates with the actuator pressure chambers at the print head output pipe is a portion of the fluid flow which is in thermal contact to the drive electronics. Excess heat, from power components and the driver ASIC driven at high frequency, is dumped into the fluid and is dissipated in the remainder of the circuit and remote reservoir.

This peripheral system works to continually condition the fluid so that at the point of use, the nozzle, it is well controlled and able to support high speed, reliable operation.

Conclusion

New approaches to the configuration of shared wall actuators open opportunities for high productivity inkjet systems with improved value propositions. Single cycle actuator configurations and print performance specifications can be readily adapted to match that demanded by printer systems.

Knowledge is available to support the efficient development of complimentary fluids and peripherals systems which are essential to the system performance as a whole.

Linear speed of the shared wall actuator is increased three times while the image quality is maintained and applications having lower image quality demands can benefit from further speed increases up to and exceeding 2.5 m/s.

References

[1] Julian Bane, Advances in Technologies for Wide Web Single Pass Printing with Piezoelectric Inkjet (IS&T, Pittsburgh, PA, September 2008).

[2] S. Temple, Patent No. EP1011975 Drop on Demand Multi-Tone Printing, App date 7th September 1998.

[3] Tri Tuladhar, Understanding inkjet inks and factors influencing the jetting behaviour (IS&T, Louisville, KY, September 2009).

[4] A. D. Paton, Patent No. EP0783410 Method of Multi-Tone Printing, App date 2nd October 1995.

Author Biography

Paul Drury is Xaar's Technology Manager, heading the technology team which undertakes the groups' fundamental research effort and leads early stage new product development activities. Drury joined Xaar in 1997 as part of the engineering team which first led Xaar in the development of its own inkjet products. Subsequent roles saw him managing relationships with key development partners and industry suppliers in the pursuit of wide array technologies and greyscale products.