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Meniscus Motion in Piezo-Drop on Demand inkjet Printing

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Abstract

In this paper we report our analyses of the fluid motions for jetting piezo-driven DoD (drop-on-demand) print-heads, having previously reported at NIP 32 our experimental data and preliminary analyses for MicroFab AB-type nozzles. Frits Dijksman introduced his non-linear analysis for piezo-DoD inkjet printing at the same conference, independently and unaware of our experimental work on MicroFab nozzles. We compare some of his predictions with our data. We have also numerically modelled the linear second-order system response and compared this with the observed MicroFab meniscus motion during and after the duration of the applied waveform. CFD modelling for these jetting experiments has also been applied to the MicroFab print-head geometry and representative properties to provide an insight into the implications for other piezo-DoD inkjet print-head geometries more relevant to industrial printing.

Introduction

Studies and analyses of meniscus motion within a piezo-DoD (drop-on-demand) inkjet print-head can be used to check basic ideas about the influences of the applied drive waveform and print-head design on jetting at higher print frequencies. For example, after ejection of a drop volume V from within the DoD nozzle, replenishment of the nozzle contents requires time before the meniscus returns to the same initial conditions as for low print frequencies. Our published experimental studies[1] of meniscus motion used tapered glass nozzles (MicroFab AB-type) in DoD mode at low printing frequencies in order to give a benchmark for determination of the nozzle refill time for different waveforms, fluids and nozzle diameters. The studies also revealed further empirical details of the fluid motion such as variations in meniscus oscillations and also nozzle overfill.

Most modern DoD inkjet print-heads are not see-through and have short (not tapered nozzles), so direct inspection of the meniscus motion within such DoD nozzles requires adoption of alternative methods. These include electrical sensing of the nozzle capacitance and laser position sensing along the jetting direction.

Theoretical models of the meniscus motion have also been presented by Frits Dijksman[2], considering both linear and non-linear effects. Despite geometric and scale differences between our studies and his models, we consider it instructive to attempt a comparison between their results and implications for inkjet printing at higher frequencies. In addition we have performed CFD computations of piezo-DoD inkjets using representative properties and geometry of the MicroFab AB-type print-head.

Experimental methods and equipment

The experimental methods and equipment used for observing meniscus motion within MicroFab AB-type nozzles were presented at NIP32 and were fully described in that paper. Sequences of high resolution images were recorded at low printing rate under each experimental condition of drive waveform duration, drive amplitude, model fluid, MicroFab AB-type nozzle diameter and applied meniscus pressure. All images were catalogued by reference to these conditions and retained for future inspection and subsequent analyses: our previous paper only reported the analyses for some of this data.

Initial empirical analyses and results

A novel visualization method was used to automatically extract the meniscus position along the jetting nozzle axis using a bespoke MATLAB code. This provided single plots, such as that shown here as Figure 1 (Figure 3 in the NIP32 report),[1] capturing the time-evolution of the meniscus motion in the jetting direction for each experimental condition analyzed. The initial empirical analysis by one of us (CSR) provided some clear insights into the variations observed with respect to waveform drive voltage amplitude and duration for given fluid, MicroFab AB nozzle diameter and applied meniscus pressure, as reported previously.

Further modifications of the MatLab code by one of us (IM) facilitated the export of the meniscus position extracted from the time sequence plots into Excel files. MS Solver could readily provide parameters for "best fits" against models for the meniscus motion, in particular the DoD meniscus oscillations which are evident in the variations in position of the light-dark boundary to the left hand side of each plot shown. The initial meniscus motion in each plot shown was produced by the leading edge of the "pull-push" MicroFab drive waveform, as labelled for 4 different "pull" pulse durations (14,16,18,20μs) with 40V drive for the same model ink (v12-10).[1] The jetting action was triggered after the leading edge of the "push" pulse.

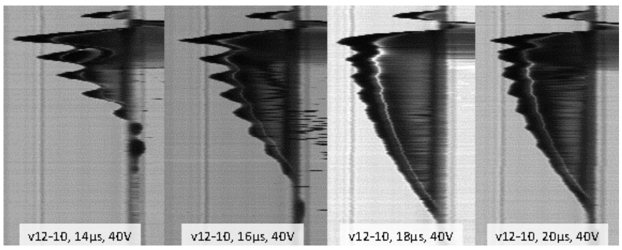

Figure 1. *Meniscus motion plots (elapsed time downwards) for 4 different piezo-DoD waveform durations (the nozzle plane lies above 40V labels)[1]*

The magnitude of the residual oscillations depended not only on the drive amplitude applied but also the pulse duration. Such pulse width dependence for resonant print-head designs is well-known and significant residual oscillation suppression here corresponded to pulse edge separation (width) of ca. 19μs, as easily seen in Figure 1 for 18μs and 20μs cf. 14μs and 16μs.

Figure 2 shows a superposition of results for the location of the fluid meniscus within the MicroFab AB-type print-head (in μm relative to the 40μm diameter exit) for 3 cases of jetting fluid (v12-10) using 18μs pulse width: 25V at 1200 or 1600Pa, and 30V at 1200Pa meniscus pressure. The 1200Pa resting position of the meniscus before jetting is shown as a green line and a dashed blue line represents the oscillatory recovery for 25V jetting. The “pull” waveform response is seen below 20µs; there is little behavioral change with meniscus pressure except within 20µm of the nozzle exit; 30V jets more fluid than 25V.

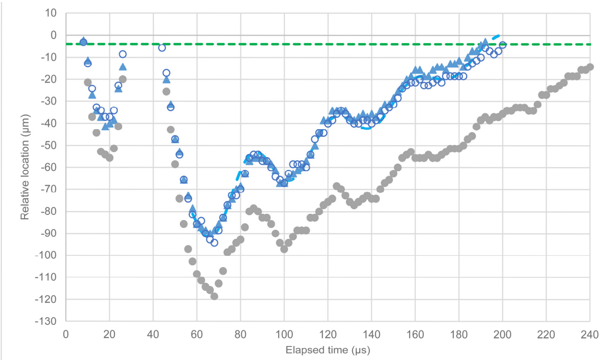

Figure 2. *Locations of the meniscus lying within a 40µm diameter nozzle MicroFab AB-type inkjet print-head used with a fixed pulse width of 18µs. The green dashed line represents the resting position of the meniscus, the oscillatory dashed line that of the meniscus motion after jetting ink, and the blue symbols the same fluid at 2 different meniscus pressures but the same drive voltage (25V); the grey symbols are for higher drive (30V).*

Figure 3 shows a superposition of results for 4 jetting examples, for fluids v12-10 or v12-23 using 25V or 30V drive at 14µs pulse width and 1200Pa meniscus pressure. Clear evidence of “overfilling” during meniscus recovery is seen at both drive voltages for the lower viscosity fluid v12-10, which at 40V with 14 and 16µs pulse widths is also seen in Figure 1.

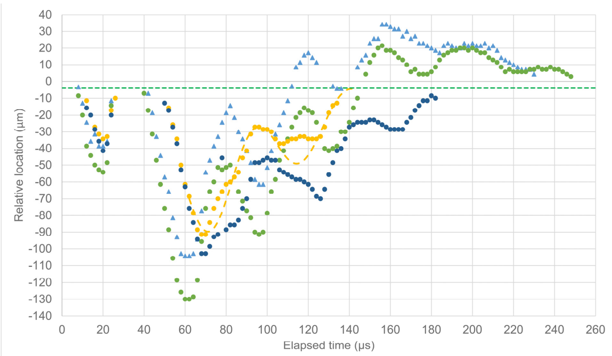

Figure 3. *Locations of the meniscus lying within a 40µm diameter nozzle MicroFab AB-type inkjet print-head used with a fixed pulse width of 14µs. The green dashed line represents the resting position of the meniscus, the light blue and green symbols are for the v12-10 fluid at 2 different drive voltages (25V and 30V); the yellow and dark blue symbols are for higher viscosity v12-23 fluid at these drive voltages and the yellow oscillatory dashed line that of the v12-23 fluid meniscus motion at 25V.*

Figures 4 and 5 reveal how meniscus recovery behavior after fluid v12-10 jetting from a 40µm diameter MicroFab AB-type nozzle at fixed pulse widths of 14µs and 16µs alters with print-head drive voltage across a higher range than those used for Figures 1-3. The differences are examined in detail later.

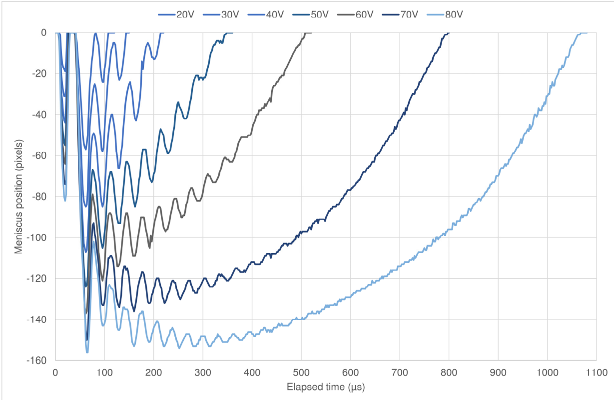

Figure 4. *Locations of the meniscus lying within a 40µm diameter nozzle MicroFab AB-type inkjet print-head used with a fixed pulse width of 14µs. Each data series, of the same general form as shown in Figures 2 and 3, corresponds to using a fixed drive voltage, in 10V steps from 20V to 80V. The elapsed timescale extends to cover the slowest nozzle refilling rate.*

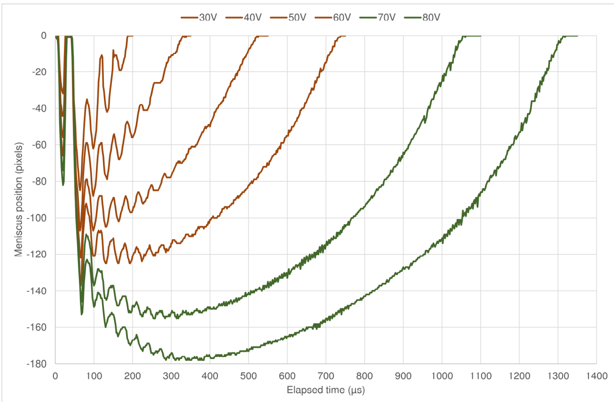

Figure 5. *Locations of the meniscus lying within a 40µm diameter nozzle MicroFab AB-type inkjet print-head used with a fixed pulse width of 16µs. Each data series, of the same general form as shown in Figure 4, corresponds to using a fixed drive voltage, in 10V steps from 30V to 80V. The elapsed timescale extends to cover the slowest nozzle refilling rate.*

Comments on these results

Both Figure 4 and 5 derive from datasets for fluid v12-10 jetted with increasing drive voltage from 20-80V in 5V steps; the intermediate curves have been removed for clarity. The waveform drive pulse appears to align the meniscus motions initially, followed by retraction dependent on drive voltage and a decaying oscillatory response superposed on slower behavior. It is readily seen that MicroFab AB-type nozzle refilling takes longer for increasing drive voltages because the meniscus has increasing withdrawn position. More subtly, this other behavior appears at lower drive voltages more like a linear ramp, while at higher voltages the meniscus actually withdraws further into the nozzle before eventually (on timescales of several 100µs) moving back towards the exit. These variations are certainly not predicted by simple models of DoD inkjet nozzle refilling.

Modeling DoD response to drive waveforms

When an inkjet system is intrinsically linear, fundamental laws allow the superposition of behaviours independently of each other. Most modelling of piezo-DoD inkjet print-head response to applied waveforms has assumed this implicitly: so here we separate the ink inlet effects from nozzle outlet effects.

In the absence of an ink inlet (ignoring nozzle refilling), DoD drop ejections must result in increasingly retracted meniscus positions within the nozzle, until the volume of the ink channel behind the nozzle is depleted of ink. Drop ejection naturally disturbs the remaining fluid within the ink channel and the nozzle from static steady state conditions and, after the applied drive waveform has ceased forcing ink motion and the jet has detached from the meniscus, free motion of the remaining ink can then follow. If the nozzle fluidic system is insufficiently damped then this results in meniscus oscillations.

These can then interfere with the production of successive drops when the printing frequency is sufficiently high. As is well known, the resonant frequency response for the piezo-DoD inkjet system is often used to lower the drive voltage required to project ink drops at typically several m/s speeds. In practice these waveforms are also designed to cancel or at least reduce the residual amplitudes of the meniscus oscillations otherwise occurring during periods between ink drop ejections, whether arising from an individual channel or neighbouring channels.[4]

Piezo-DoD inkjet print-heads having an inlet restrictor as well as the nozzle outlet were modelled previously by Frits Dijksman and others[5]. Such systems naturally introduce an ink refill timescale after DoD drop ejection, due to the presence of the inlet. MicroFab AB-type inkjet print-heads should have a much longer refill time than that for modern industrial piezo-DoD print-heads, thereby providing a means to measure this refill effect in our studies. Appropriate scaling laws can then be applied to predict refilling timescales for industrial print-heads, which will impact on the likely maximum printing frequencies.

Assuming the linearised equations for the ink motion in and associated with the nozzle, solutions for time evolution of meniscus motion (position and axial speed) within a cylindrical nozzle for some applied waveforms were previously derived.[5] The steady state and burst printing frequency responses for DoD inkjet printing for very short duration waveforms under both conditions were modelled using these linear solutions (corrected by SDH for typos in the printed version[5]) and results appear consistent for different print-heads and fluids.[6]

The correct linear solutions are now used to analyse the expected meniscus response for the "pull-push" piezo-DoD drive waveform durations 12,14,16,18 or 20µs used in the experimental study.[1] The duration of the "push" was always twice that of the initial "pull" , with 2µs rise and fall times on all edges irrespective of equal "push-pull" drive amplitudes. These edges are so fast that the waveform could be considered as providing step changes rather than ramps, which simplifies the mathematics of the following discussion, although the full equations given in the appendix could be applied if necessary.

Frits Dijksman[2] introduced a non-linear treatment of inkjet printing at NIP32. His predictions include a nozzle exit pinned meniscus position-dependent surface tension term only valid very close (within 1 quarter of the nozzle radius) of the nozzle exit. For our studies with 40µm diameter MicroFab nozzles this represents locations within 5µm (ca 3 pixels) of the nozzle exit, Therefore effects arising this particular correction are unresolvable for typical DoD inkjet print-head nozzle sizes.

Empirical analyses and results

As the MicroFab AB-type inkjet nozzle has an internal taper rather than a short length of conical or cylindrical profile, and the meniscus shape is dynamic, the axial meniscus position is not a direct measure of the volume of ink within the nozzle. These factors both complicate the determination of the missing volume, so we measured the nozzle profiles optically and then parameterised them using a hyperbolic tangent radial profile[3] shape R(z), where the nozzle exit is located at z=0 and the axial positions inside satisfy z<0, can be described by Equation (1).

$$R(z) = a - b \tanh [(z-z_1)/z_0] \qquad (1)$$

Two fit parameters (a and b) represent combinations of the radial extremes for the nozzle, while the others (z_1 and z_0) represent the centre and extent of nozzle tapering. This shape was fitted to optically assessed profiles for each MicroFab AB-type nozzle diameter used in our meniscus motion studies. Our CFD computations also used this nozzle shape representation.

Using the observed axial meniscus position and additional curvature measurements for some series of plots and original images showed that the determination of missing volume from the axial positions alone was sufficient for the present purposes, and therefore the analyses presented here use the plots alone.

Plots of meniscus position such as shown in Figure 1 were converted by integration to produce "missing volume" plots, whereas for CFD such volumes could be extracted exactly by numerically tracking the interface. This numerical model enabled us to investigate the assumption that the meniscus remains pinned to the nozzle exit, and also relates the motion of the meniscus to refill and recovery mechanisms. Unfortunately this could not be observed reliably within the recorded images.

The "missing" volume can be converted to an equivalent meniscus position in other nozzle geometries, such as within cylindrical nozzles of specific diameter, for comparison with predictions of meniscus motion by linear[4] and/or non-linear modelling[2] and also linear modelling of the fluid in the print-head nozzle based on a single mode mechanical resonance response.[5] In addition our results can be used to predict the expected printing frequency response using an impulse approximation.[6]

CFD modelling and results

Numerical modelling using a commercial finite element-based code has been used to help identify the mechanisms involved in meniscus dynamics. A 2D axisymmetric fluid structure interaction (FSI) model of the MicroFab print-head was developed, with the meniscus dynamics modelled using a conservative level set method to represent the moving interface. The electrical impedance characteristics of the piezoelectric element coupled to the system when either wet and dry were compared with measurements taken on an impedance analyzer. This comparison confirmed that the model correctly predicts the Helmholtz mode of the ink-primed (wet) system.

The CFD model has been used for characterization of the system based on the same parameters investigated in the laboratory experiments, with parametric sweeps of voltage, pulse width and fluid parameters. Whilst the operational characteristics of the MicroFab nozzle are far removed from the high frequency jetting processes currently being developed in high resolution, high performance industrial inkjet print-heads, this model can also be useful for benchmarking the multi-physics modelling used in product development because meniscus behaviour inside the nozzle itself can be directly compared with the observed MicroFab nozzle dynamics. In commercial print-heads, the retracted meniscus is obscured due to the nozzle plate and can only be located by indirect means.

In general, the model over-predicts the actuation efficiency (droplet momentum is predicted to be too high with respect to the voltage amplitude), but qualitatively gives useful insight into the refill mechanisms and it is possible to observe similar trends in the time history response of the meniscus position inside the nozzle. Differences in actuator efficiency could be attributed to errors in the assumed piezo coefficients, loss factors in the elastic layers and limited knowledge of adhesive layers in the device construction.

Figure 6 plots the volume contained in the nozzle region, as a function of time and for different voltage amplitudes, using v12-10 fluid and 14µs pulse width. The volume in the nozzle is calculated precisely by integrating the level set function in the domain of the nozzle region. Unlike the experimental data, where the on-axis meniscus position was tracked, the fill-fraction of the nozzle is a more useful metric in the CFD data because it is currently impossible to stop the attached ligature from biasing the numerical meniscus position during the droplet evolution process.

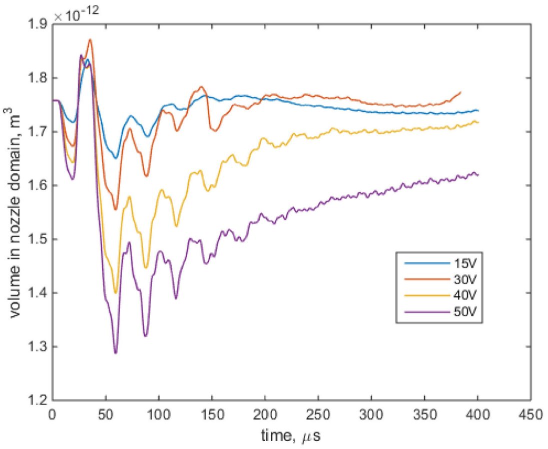

Figure 6. *Volume of v12-10 ink in the 40µm MicroFab AB nozzle as a function of elapsed time in response to the applied voltage amplitude at 14µs print-head drive pulse width. These curves were computed by integration over the CFD meniscus shape as described in the text.*

Comparing with the experimental data in Figure 4, it is apparent that the model identifies different modes of recovery of the meniscus, dependent on the actuation amplitude. In common with the experimental evidence, at lower amplitude, the recovery is dominated by a fast refill that could be attributed to surface tension capillary pressure forces. At later times (e.g. after 150µs for the 15V actuation) overshoot of the meniscus is observed, with the refill mode frequency clearly oscillating once the Helmholtz acoustic frequency has been attenuated. As the voltage is progressively increased, the time constant for refill appears to increase, perhaps suggesting that the meniscus behaviour differs from the simple capillary refill discussed above. Note that the general shape of the meniscus recovery is different compared with the empirical data during the later period of the refill process, for the higher actuation amplitudes. In the empirical data measured in units of meniscus position, the meniscus speed appears to increase towards the final stages. In these numerical data, the rate of recovery of the volume of the nozzle appears to reduce towards the equilibrium position. Some of these differences can be attributed to the nozzle taper and its influence on the meniscus position, although efforts are currently underway to improve our understanding of the dynamic refill mode.

Some comparisons with Dijksman's results

In the NIP32 conference contribution[2] Frits Dijksman provided the analysis for a "push" mode piezo-DoD inkjet print-head, where the ink moves outwards immediately as the leading edge of the drive waveform is applied, in a short cylindrical nozzle. The waveform he used had 0.1µs rise time and 25µs fall time and a 3.4µs duration pulse. For the experiments that we had presented at NIP32,[1] a standard DoD "pull-push" mode MicroFab waveform with 2µs edges and 1:2 dwell to echo times and tapered AB-type nozzles were used, so that some differences between results are clearly to be expected.

Specifically, the flow line differentials for our tapered geometry would be smaller than for a conical inlet to a cylindrical nozzle. Our inkjet experiments primarily used inks (v12-10 & v12-23) with higher viscosity (>0.01Pas) than those (0.005 & 0.002Pas) of Dijksman, who noted slosh mode influenced 0.002Pas jets. His computations showed extremely slow meniscus return to the nozzle exit once it was within 3.75µm of the exit, which would be unresolvable with reliability in our experiments. In our experiments, shorter pulse width durations were poorly matched to reduction of residual wave amplitudes and also produced rapid over-filling of the nozzle, not predicted by Dijksman for his inkjet system. Longer pulse widths were better matched to reduce residual oscillations at the expense of longer refilling timescales in our experiments.

Conclusions

A direct comparison between results for the piezo-DoD inkjet print-head designs used by Fritz Dijksman and ourselves seems rather fruitless because of their major differences, but these studies were independent and with rather different foci. However the linear second order system theory at the heart of earlier work[5], and my more recent modelling[6], still appears to provide a suitable basis for analysis of low frequency printing, as exemplified by the modelling results shown in the Appendix.

Analysis of our own experiments revealed increasing long meniscus position recovery times and also an apparent change of refill mechanism after single shot printing as the piezo drive voltage was raised from just below to far above the DoD jetting threshold. Specifically, at voltages increasingly above jetting threshold, nozzle refilling had an early period of increasingly retracted mean positions (time-averaged over residual oscillations) prior to an eventual return towards the nozzle exit. Such behaviour is decidedly non-linear, irrespective of the non-cylindrical (but monotonically tapering) inkjet nozzle shape. At shorter "pull-push" pulse widths the nozzle refill mechanism(s) could be sufficiently under-damped that the nozzle over-filled. This condition might be associated with the mismatch between drive pulse and the fluidic system cavity resonant frequency, which produces large residual oscillations, if "slosh" mode got excessive excitation and/or lower damping factor as a result. The 1.2kPa or 1.6kPa static retaining pressures applied to the print-head ink reservoir had little effect on the observed DoD jetting speed, tail speed or the meniscus motion.

Our extensive experimental dataset has already provided a wealth of insights into meniscus motion within piezo-DoD print-heads, with further analyses to be published in the future.

Appendix

The step response of a linear second-order system having a damped natural frequency $\omega_d=\omega_n\sqrt{(1-\zeta^2)}$ and initially at rest is

$$y/X = 1-\exp(-\zeta\omega_n t)\cos(\omega_d t-\psi)/\cos(\psi) \quad (2)$$

See, for example, University of Cambridge undergraduate data book.[7] The damping constant is $\zeta<1$, natural frequency ω_n, phase shift ψ has $\sin(\psi)=\zeta$ and the step magnitude X ($t\geq0$) follows X=0 ($t<0$) normalises response y. For most DoD inkjet print-head designs the damping factor $\zeta \ll 1$, so that $\omega_d\approx\omega_n$ and

$$y/X = 1-\exp(-\zeta\omega_n t)\cos(\omega_n t) \quad (3)$$

This damped cosine form of the system response was adapted for the multi pulse train model for piezo-DoD printing, as described elsewhere,[6] and ignoring a phase shift is similar to the impulse approximation result expected for this system.[7]

The response at time $t \geq 0$ of the same linear second-order system to a ramping rate of X over $\Delta>0$ starting at t=0 is not so easily expressed. The changed initial conditions ending a ramp period need not be ignored (stated by Dijksman and Pierik,[5]);

$$y/X = t/\Delta - 2\zeta/\omega_n\Delta + \exp(-\zeta\omega_n t)\{(y_0/X + 2\zeta/\omega_n\Delta)\cos(\omega_d t) - (v_0/\omega_n\Delta + \zeta y_0/X - (1-2\zeta^2)/\omega_n\Delta)\sin(\omega_d t) / \sqrt{(1-\zeta^2)}\} \quad (4)$$

The response at time $t \geq \Delta$ after the ramping stopped is given by

$$y/X = 1+ \exp(-\zeta\omega_n t)\{[\cos(\omega_d t)-\exp(\zeta\omega_n\Delta)\cos(\omega_d(t-\Delta))](2\zeta/\omega_n\Delta) + [(y_{0a}/X)\cos(\omega_d t) - (y_{0b}/X)\exp(\zeta\omega_n\Delta)\cos(\omega_d(t-\Delta))] - (v_{0a}/\omega_n\Delta + \zeta y_{0a}/X - (1-2\zeta^2)/\omega_n\Delta)\sin(\omega_d t) /\sqrt{(1-\zeta^2)} + (v_{0b}/\omega_n\Delta + \zeta y_{0b}/X - (1-2\zeta^2)/\omega_n\Delta)\exp(\zeta\omega_n\Delta)\sin(\omega_d(t-\Delta)) /\sqrt{(1-\zeta^2)}\} \quad (5)$$

The 0a and 0b suffixes refer to initial values of y and v=dy/dt at the start and end of the ramp duration Δ, normally all assumed 0.[5] Trigonometric expansions of $\cos(\omega_d(t-\Delta))$ and $\sin(\omega_d(t-\Delta))$ can be used to separate the $\cos(\omega_d t)$ and $\sin(\omega_d t)$ terms as usual. The long term effects of initial conditions always decay exponentially and the magnitude of the residual oscillations caused by a single ramped edge depend on the time duration Δ, the natural frequency ω_n and the damping factor ζ.

The same approach can be used to determine the linear second-order system response to any number of ramping periods, even for complex waveforms such as used for greyscale printing, provided the appropriate allowances are made for droplet production, jet separation and drop merging, although such considerations are beyond the scope of the paper.

A numerical summation of time-shifted ramps assuming zero initial conditions for each ramp (of 6 required for the standard "pull-push" waveform shape) was used to compare with the actual response of the MicroFab AB 40µm print-head for a DoD "pull-push" waveform at 25V and 18µs pulse width. Figure 7 shows this captures the initial "pull" phase quite well: the resting position for 1200Pa backing pressure was ignored in the summation). The snap-back of the meniscus position just following jet formation, corresponding to ink volume ejection from the nozzle, alters the phase and magnitude of the residual oscillations of the meniscus following the end of the waveform. The altered initial location and speed of the meniscus, and the subsequent refill are not included in the numerical summations.

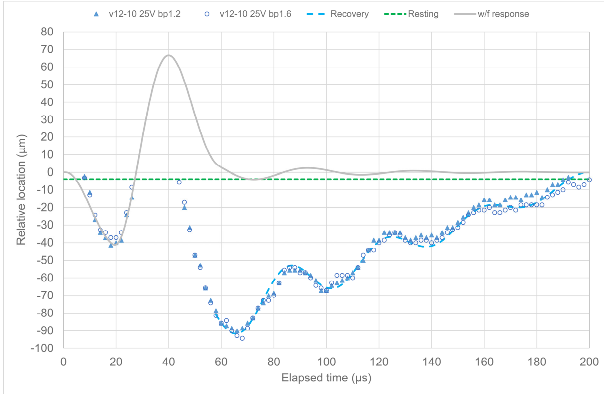

Figure 7. *Comparison between actual and predicted responses for the 40µm MicroFab print-head with 25V & 18µs DoD "pull-push" waveform, ignoring the resting meniscus offset on the waveform ("w/f") response. Differences between the data for 1.2kPa and 1.6kPa are rather small.*

Acknowledgements

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Author Biography

Stephen D Hoath recently completed his contract with the University of Cambridge, Department of Engineering Institute for Manufacturing Inkjet Research Centre, after 12½ years on inkjet printing. He edited the book on Fundamentals of Inkjet Printing: The Science of Inkjet and Droplets for Wiley-VCH. He works on new international (IEC/ISO) standards for inkjet equipment for printed electronics. He is a Fellow of Wolfson College Cambridge and the Institute of Physics and frequent contributor to the NIP conferences and recent member of the Society of Imaging Science and Technology.