Cross-Talk Reduction by Smart Delay Firing

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Abstract

As ink jet arrays become larger, the cross-talk between closely spaced firing channels becomes more severe resulting in an adverse impact on print quality. A method of addressing this problem applicable to any type of DOD ink jet without making any physical changes to the individual jet design and with only minimal changes to the array configuration is described.

The individual channels of the array are divided into N interspersed groups and the permitted firing time of each group has its own small time delay, δ. An optimum delay is calculated for each group so that, when all channels are fired, there is a maximum amount of cross-talk cancellation. Because the firing channels are the source of an acoustic wave train predominantly at a resonant frequency of the channel, the interaction with other firing channels depends strongly on the phase relationship with the arriving wave. For any given print-head, a number of basic experimental measurements are made and the data used as input to a computer model, which calculates the change in drop velocity as a function of the delays for a channel near the centre of the array when all channels are firing. The basic equations and an outline of the computation are shown.

I. Introduction

In most, if not all, drop-on-demand multi-channel ink-jets, the simultaneous or near simultaneous firing of jets results in an interaction between the jets commonly referred to as cross-talk. Typically cross-talk is seen as a change in drop volume, drop velocity and details of the ligament structure, all of which affect the size, position and shape of the printed dot. In this paper, the problem is simplified by just using the change in drop speed of a jet as a measure of the degree of cross-talk. Although this is a somewhat arbitrary choice, it has been seen experimentally that actions taken to reduce changes in drop speed also result in smaller changes in drop volume, straighter jets and smaller changes in the ligament structure. If the speed of a drop is V and the cross-talk induced variation is ΔV, the resulting dot placement error, ΔX just from the speed change is given by:

$$\Delta X = ABS[gV_s\Delta V/\{V(V+\Delta V)\}] \quad (1)$$

where g is the paper gap and V_s is the paper speed past the print-head. This shows that larger absolute placement errors are caused by negative ΔVs than by positive ΔVs of the same magnitude i.e. negative cross-talk is worse than positive cross-talk. Empirically it has been found that it is possible to specify limits on the maximum allowable positive ΔV_1 and the maximum allowable negative ΔV_2 where $\Delta V_1 > \Delta V_2$. The limits can be specified such that, if V lies within this range, print quality will be acceptable.

Most attempts to address the cross-talk problem have involved designing the print-head to minimize the coupling between channels. These methods are therefore usually specific to the particular type of print-head design. Moreover, the methods are also frequently specific to a particular cross-talk path. In most cases the coupling between channels can occur via several different routes. For example in an ink jet of the piezo-electric length expander type, it has been seen that cross-talk can occur via a fluidic path through the ink because of a common manifold,[1] via the print-head housing because of a common mounting structure for the piezo-electric drivers[2] or via a common flexible diaphragm which is used to couple the piezo-electric driver motion into the ink chamber. In many cases, design changes to reduce the coupling result in an undesirable reduced packing density of channels. Also in today's high density large arrays cross-talk is particularly severe.

Typically, the print-head can be considered as an array of coupled identical channels each of which is a mechanical and/or fluidic oscillator with one or more resonant frequencies. Consider now what happens if just one channel in the array, a "transmitter", is fired. It executes a damped oscillation which is coupled in turn to all the other channels, the "receivers", in the array. The array may thus be thought of as a sort of delay line propagating the cross-talk disturbance. The cross-talk disturbance travels at a speed which is lower than the speed of sound in the print-head structural materials for structural cross-talk or, in the ink, for fluidic cross-talk. Each receiver has a resonance(s) which is readily excited by the cross-talk disturbance and thus executes an oscillation which builds up over a few cycles before decaying. The oscillation becomes weaker for more distant receivers and there is also a greater delay.

If a receiver is also fired at the same time as the transmitter, the cross-talk disturbance can be considered as being added to the firing disturbance. The resulting change in speed of the drop will depend not only on the magnitude of the cross-talk disturbance but also on the phase. If the phase (time delay) alone is changed, the cross-talk disturbance will go through cycles of adding to or subtracting from the driver disturbance thus resulting alternately in either positive or negative cross-talk with the magnitude of the cross-talk becoming weaker for larger time delays. The periodicity of the cross-talk variation with time delay will depend on the channel resonances. For example, in the ink jet used in the experimental work for this paper, there was a dominant chamber or Helmholtz resonance at about 70 kHz. The cross-talk variation was roughly sinusoidal with a period of about 14 μsec. For a cross-talk disturbance arriving after the receiver has fired, there is only any cross-talk effect up until the time that the forming drop is essentially decoupled from the jet. In the print-head used for the experiments in this paper, this time was about 15 μsec.

II. Concept of Phased Firing to Reduce Cross-Talk

In the first description of phased firing by Lahut,[3] the channels were divided into two interlaced groups, odd and even numbered channels. As it was recognized that cross-talk was most severe for adjacent channels, the concept was to separate the firing times by as much as possible. In practice this time separation was one half of the minimum time between firings called for in the printer. Thus, for a print-head having a maximum firing frequency of 10 kHz, the firing time separation between adjacent channels was 50 μsec. This relatively large delay would have resulted in a non-negligible dot placement error and hence this was compensated by making an orifice plate with a shift in the position of one group of orifices. This concept was called “two phase firing” and was later developed into three and four phase firing with interlaced three and four groups of channels. This method was successful in reducing cross-talk in arrays of 32 channels with a channel spacing of about 0.7mm.

In the new concept described here,[4] the channels are also divided into a number of interlaced groups, with each group having its own phase or firing delay, but it is recognized that, for much shorter delays, the phase of the cross-talk disturbances arriving at a receiver channel will depend upon the firing time delay and also the distance away of the transmitting channel. The cross-talk phase from different transmitters can easily vary enough that some cross-talk contributions will be negative and others positive. The objective is to calculate delays from experimental data such that the sum of all the contributions will result in cross-talk cancellation. The degree of cancellation will depend upon the number and positions of the firing channels and will also vary for each “receiver” channel. The calculation is therefore made for the case where all channels are firing which is usually close to the worst case for uncorrected cross-talk. The degree of cancellation will also depend upon the frequency of firing when the frequency becomes high. Raw data have been obtained and calculations made for the following cases:

- 2 phase low frequency.
- 2 phase high frequency.
- 3 phase low frequency, unequal delays.
- 3 phase high frequency, unequal delays.

The outline and some results of the calculations are given together a guide to how it can be extended to the general case for N phases.

III. Basic Assumptions and Definitions of Symbols and Terms

To reduce the amount of data needed and to simplify the calculations, the following basic assumptions are made:

(1) Cross-talk is algebraically additive. If a “receiver” channel, firing a drop with speed, V, changes in speed by an amount ΔV_a when another channel, a, is fired, the cross-talk is defined as $\Delta V_a/V$. When other channels are firing, the total cross-talk, $\Delta V/V$, is given by:

$$\Delta V/V = \Sigma \Delta V_a/V$$

This is true if $\Delta V/V << 1$. This assumption was tested using experimental data and found to be reasonably good if $\Delta V/V$ </= 0.1.

(2) All channels are identical and, when no other channels are firing, each channel is assumed to have a speed, V, which is the same for all channels. End channel effects are ignored.

(3) The time delay, δ, between two phases is defined as the time by which a “transmitter” channel fires after a “receiver” channel. The cross-talk contribution from any channel is zero for δ >/= 15 μsec.

(4) The print-head is assumed to be a linear array of channels. For N phase firing, the channels are divided into N groups, 1,2……N, each group having its own delay. Group 1 or phase 1 is defined as the first group to fire. The channels are arranged in groups as follows:

1, 2, 3, ……N, 1, 2, 3, ……N, 1, 2, 3, ……

The delay between phase 1 (receiver) and phase 2 (transmitter) is δ_1 and between phase 2 (receiver) and phase 3 (transmitter) is δ_2 and so on.

(5) If the firing frequency, f, is sufficiently low that the effect of previous firing has no effect on any phase in the current firing, then frequency can be neglected. The minimum time, t, between adjacent firing cycles will be given by:

$$t = (1/f - \delta_{max})$$

where δ_{max} is the maximum delay between any two phases.

From experimental data, it has been seen that for t >/= 300 µsec, the previous firing can be ignored. If it is assumed that δ_{max} is small, then the low frequency range will be below 3 – 4 kHz.

(6) In general, with all channels firing, each phase group will have its own drop speed and therefore, its own dot placement error, ΔX. An overall cross-talk rating for the print-head is defined by a "figure of demerit", F. F is a weighted average of the dot placement errors. If ΔX_N is the value of ΔX for phase N, The value of $F(\delta_1, \delta_2, \ldots)$ is given by:

$$F = (w_1.\Delta X_1 + w_2.\Delta X_2 + \ldots + w_N.\Delta X_N) / N \quad (2)$$

where the ws are weighting factors.

The weighting factor is used to increase the impact of any ΔX on F if ΔX is greater than some selected value, e, of the maximum acceptable dot placement error. For example, if a simple linear weighting is used:

$$\text{If } \Delta X =/< e, \quad w = 1$$

$$\text{If } \Delta X > e, \quad w = k$$

Increasing k will make F more responsive to the condition, ΔX > e. For initial calculations, a value of k = 2 was used.

(7) It is assumed that the best values of δ will be those that give values of F less than e or, if F is always greater than e, as low as possible over a reasonably wide range of δ. The lowest value of F might not necessarily be the best choice if it occurs as a sharp minimum. This is because of considerations of variability in the data. There may also be a preference for choosing smaller values of δ that gives a low F because the delay itself results in a dot placement error. For larger values of δ, it is necessary to correct this with an offset of the orifice position. This requires specially made orifice plates.

The above assumptions can be expressed symbolically if we denote the ΔV in phase group, p, by all channels firing in phase groups, p, q, r…. as $\Delta V_{(p, p \& q \& r \ldots)}$. In general this will be a function of the values of δ between the phases.

$$\Delta V_{(p, p \& q)}(\delta) = \Delta V_{(q, p \& q)}(-\delta)$$

$$\Delta V_{(p, p)} = \Delta V_{(p, p \& q)}(\delta = 15)$$

$$\Delta V_{(p, p)} = \Delta V_{(q, q)} = \Delta V_{(r, r)} = \ldots\ldots$$

$$\Delta V_{(p, p \& q \& r \& s \ldots)} = \Delta V_{(p, p \& q)} + \Delta V_{(p, p \& r)} + \Delta V_{(p, p \& s)} + \ldots - (n-2)\,\Delta V_{(p, p)}$$

For 3 phase firing, there are also additional symmetries from which it follows that, if the delay between phases 1 & 2 is δ and the delay between phases 2 & 3 is Mδ:

$$\Delta V_{(1, 1 \& 2)}(\delta) = \Delta V_{(2, 2 \& 3)}(M\delta)$$

$$\Delta V_{(1, 1 \& 2)}(\delta) = \Delta V_{(1, 1 \& 3)}(\{1+M\}\delta)$$

If the effect of firing frequency, f, is taken into consideration, this is indicated symbolically by an additional bracketed suffix. Thus the ΔV in a receiver channel in phase group, p, caused by all channels firing at a frequency, f, in phase groups, p, q, r…. is denoted as $\Delta V_{(p, p \& q \& r \ldots)(f)}$.

IV. Calculation of Optimum F for Specific Cases

(a) Two Phase (Low Frequency)

Minimal experimental data obtained was the drop speed, V, of a phase 1 channel near to the centre of the print-head firing alone and the drop speed, $V_{(1,1\&2)}(\delta)$ of the same phase 1 channel with all phase 1 & 2 channels firing over a range of δ from +20 to –300 µsec. Other input data for the calculation were g = 1.5mm, V_s = 2M/sec, e = 25microns and k = 2.

For the two phase, low frequency case, the figure of demerit from equation (2) becomes:

$$F(\delta) = (w_1\Delta X_1 + w_2\Delta X_2)/2 \quad (3)$$

ΔX_1 and ΔX_2 from equation (1) become:

$$\Delta X_1 = ABS[(gV_s\Delta V_{(1,1\&2)})/\{V(V+\Delta V_{(1,1\&2)})\}] \quad (4)$$

and,

$$\Delta X_2 = ABS[(gV_s\Delta V_{(2,1\&2)})/\{V(V+\Delta V_{(2,1\&2)})\}]$$

$\Delta V_{(2,1\&2)}$ is obtained from the experimental data, $V_{(1,1\&2)}(\delta)$ and V from the following relationships:

$$\Delta V_{(2,1\&2)} = \Delta V_{2,1} + \Delta V_{2,2}$$

$$\Delta V_{2,2} = \Delta V_{1,1}$$

$$\Delta V_{2,1}(\delta) = \Delta V_{1,2}(-\delta)$$

$$\Delta V_{1,2} = \Delta V_{(1,1\&2)} - \Delta V_{(1,1)}$$

$$\Delta V_{(1,1)} = \Delta V_{(1,1\&2)}(\delta_1 = 15)$$

Using these relationships, equation (3) and (4) were used in a spreadsheet calculation to compute the figure of demerit as a function of delay, δ (see Fig. 1).

Figure 1 shows a cyclic variation in F with a period of 14 to 17 µsec which is close to the period of the Helmholtz resonance. There are minima in F at approximately odd numbers of half Helmholtz periods and maxima at intervals of the Helmholtz period. There is clearly an optimum delay at about –8.5 µsec where F, a weighted average of dot placement error, has a value of about 6 microns. Other minima in the curve are not as low and are also less desirable because the greater magnitude of the delay would make a stronger need for a compensated orifice plate. At a delay magnitude of 8.5 µsec and a paper speed of 2 M/sec, the orifice position compensation needed is just 17 microns. In this case, this is less than the assumed value of e, 25 microns, for the maximum acceptable dot placement error which might make a compensated orifice plate unnecessary.

The significant improvement over the case where all channels are firing synchronously is seen from the value of F at zero delay of about 340 microns. A comparison can also be made with the two phase version of the method described by LaHut[3] in which the delay between adjacent channels is set to be as high as possible which is one half of the period of the maximum frequency. For maximum frequencies up to about 50 kHz, F varies from about 50 microns to 150 microns except in the frequency range from about 28 kHz to 42 kHz where it reaches up to 280 microns.

The curve clearly shows the cyclical variation in F. Starting from zero delay, the first cycle has a period of about 14 µsec which corresponds closely with the chamber or Helmholtz resonance for this print-head of about 70 kHz. It appears that the cycle period increases up to about 17 µsec for greater delay magnitudes. The reason for this is not clear but it may be related to measurements of cross-talk propagation speed which show an apparent slowing down as time increases.

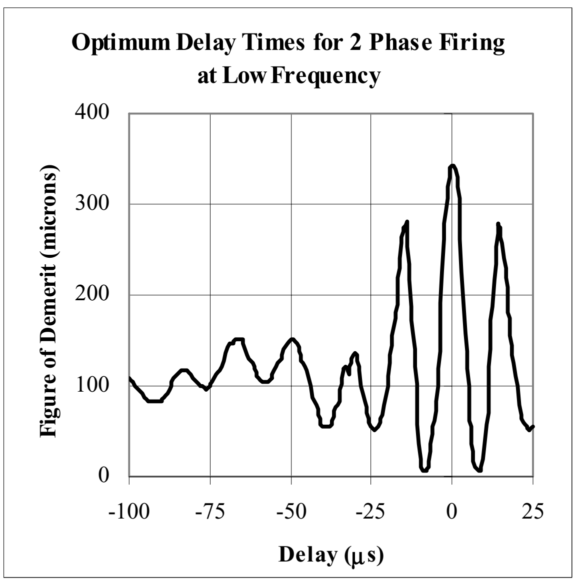

Figure 1. Figure of demerit showing an optimum delay range of 7 – 10 µsec for two phase low frequency firing.

(b) Two Phase (High Frequency)

The minimum experimental data needed is the same as for low frequency case plus $V_{(1,1)(f)}$ – i.e. the velocity of the same "receiver" phase 1 channel with just all phase 1 channels firing measured as a function of frequency over the desired frequency range. The objective is to calculate F(δ, f) from these input data. In general to calculate F at any frequency, it is first necessary to compute $\Delta V_{(1,1\&2)(f)}(\delta)$ and $\Delta V_{(2,1\&2)(f)}(\delta)$. The low frequency calculation must be modified to include the contributions from previous firings. The steps are:

(1) $\Delta V_{(1,2)(0)}(\delta)$ is calculated as described for the low frequency case.

(2) Evaluate equations (5) – (7):

$$\Delta V_{(1,2)(f)}(\delta) = \Delta V_{(1,2)(0)}(\delta) + [\Delta V_{(1,2)(0)}(\delta - 1/f) + \Delta V_{(1,2)(0)}(\delta + 1/f)] + [\Delta V_{(1,2)(0)}(\delta - 2/f) + \Delta V_{(1,2)(0)}(\delta + 2/f)] + [\Delta V_{(1,2)(0)}(\delta - 3/f) + \Delta V_{(1,2)(0)}(\delta + 3/f)] + \ldots + [\Delta V_{(1,2)(0)}(\delta - (n-1)/f) + \Delta V_{(1,2)(0)}(\delta + (n-1)/f)] \quad (5)$$

$$\Delta V_{(1,1\&2)(f)}(\delta) = \Delta V_{(1,2)(f)}(\delta) + \Delta V_{(1,1)(f)} \quad (6)$$

$$\Delta V_{(2,1\&2)(f)}(\delta) = \Delta V_{(2,1)(f)}(\delta) + \Delta V_{(2,2)(f)} \quad (7)$$

(3) $\Delta X_1(\delta,f)$ and $\Delta X_2(\delta,f)$ are calculated in the same way as for f = 0 but the calculation is now repeated for a number of values of f. F(δ,f) is now calculated in the same way as for f = 0 for each value of f. In practice the values of f chosen may be limited to just the frequencies that can occur in a printer. For example if the maximum possible firing rate is at f_{max} then the series of discrete frequencies possible is;

$$f_{max}, f_{max}/2, f_{max}/3, \ldots\ldots f_{max}/n$$

(c) Three Phase (Low Frequency)

Because of symmetries in the 3 phase case resulting from the assumption that all channels are identical, the minimal experimental data needed is only V and $V_{(1,1\&2)}(\delta)$ - all phase 1 and phase 2 channels firing measured over a range of δ from +20 to –300 µsec. However, because there are now two delays, δ between phases 1 & 2, and Mδ between phases 2 & 3, the calculated F will be a function of two variables, δ and M. This can either be displayed as a 3 dimensional surface or as a number of superimposed 2 dimensional plots of F vs. δ with the parameter M being changed for each plot.

The calculation steps are similar to the two phase case but with the following additional symmetry relations:

$$\Delta V_{(1,1\&3)} = \Delta V_{(1,1\&2)}(\{1+M\}\delta) \quad (8)$$

$$\Delta V_{(1,1\&2\&3)} = \Delta V_{(1,1\&2)} + \Delta V_{(1,1\&3)} - \Delta V_{(1,1)} \quad (9)$$

$$\Delta V_{(2,2\&3)} = \Delta V_{(1,1\&2)}(M\delta) \quad (10)$$

$$\Delta V_{(2,2\&1)} = \Delta V_{(1,1\&2)}(-\delta) \quad (11)$$

$$\Delta V_{(2,1\&2\&3)} = \Delta V_{(2,2\&3)} + \Delta V_{(2,2\&1)} - \Delta V_{(2,2)} \quad (12)$$

$$\Delta V_{(1,1)} = \Delta V_{(2,2)} = \Delta V_{(3,3)} \quad (13)$$

$$\Delta V_{(3,3\&2)} = \Delta V_{(1,1\&2)}(-M\delta) \quad (14)$$

$$\Delta V_{(3,3\&1)} = \Delta V_{(1,1\&2)}(-\{1+M\}\delta) \quad (15)$$

$$\Delta V_{(3,1\&2\&3)} = \Delta V_{(3,3\&2)} + \Delta V_{(3,3\&1)} - \Delta V_{(3,3)} \quad (16)$$

$$F = (w_1\Delta X_1 + w_2\Delta X_2 + w_3\Delta X_3) / 3 \quad (17)$$

Figure 2 shows the results of a calculation of F for equal delays (M = 1) using data from the same print-head as was used for the two phase calculation (Fig. 1). Other input data for this calculation were the same as used for the two phase case; g = 1.5 mm, V_s = 2M/sec, e = 25 microns and k = 2.

Comparing with the two phase case, there is still a cyclic variation approximately at the Helmholtz resonance but the variation is somewhat lower and F is lower at large delays. The large delays are only of academic interest, the main region of interest being in the ranges around 8 μsec and around 24 μsec. In the 24 μsec range, the three phase case has a range from about 20 to 27 μsec where F is 25 microns or less. This is clearly an improvement over the two phase case where there is a minimum F of 50 microns just at 24 μsec. In the 8 μsec range however the comparison is not so clear. In the two phase case there is a minimum value of F of about 6 microns compared with 27 microns for the three phase case. However there is a greater range (4 to 11 μsec) in the three phase case compared with (6 to 10 μsec) in the two phase case where F is 50 microns or less.

At zero delay, all channels firing synchronously, the value of F is about 480 microns. This is higher than the zero delay value of F in the two phase case, 340 microns. The reason for this discrepancy is that, in the two phase case $V(\delta=0)$ is measured directly $V_{(1,1\&2)}$, whereas in the three phase case, $V_{(1,1\&2\&3)}$ is calculated from the experimental data which is $V_{(1,1\ \&\ 2)}$. The discrepancy is thus reflecting some inexactitudes in the basic assumptions.

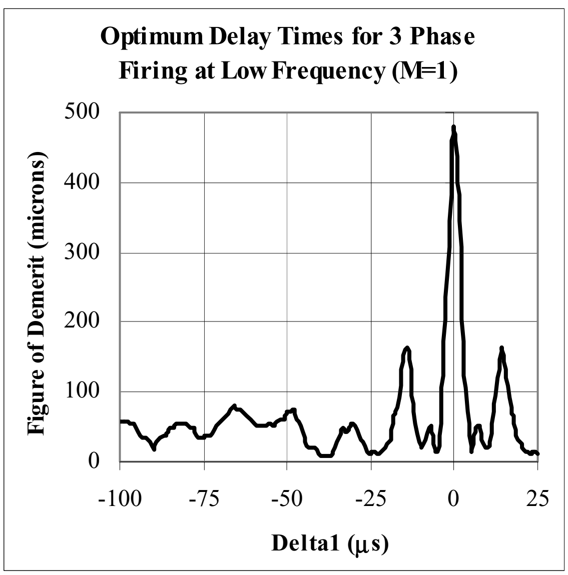

Figure 2. Figure of demerit for three phase low frequency firing.

(d) Three Phase (High Frequency)

The additional experimental data needed is just the frequency data, $V_{(1,1)}(f)$ and the calculation follows a similar route to that outlined for the two phase case. Computations of F made over the frequency range 4 to 22 kHz are shown in Fig. 3. The experimental data for these computations was taken from a print-head being used by a client who needed to reduce cross-talk. This print-head was used with a different ink and has some modifications making it somewhat different from the print-head used for Figs. 1&2. For the calculation in Fig.3, the following input variables were also changed: g = 0.8 mm, V_s = 0.42M/sec, e = 10 microns.

This shows that there is a trend for cross-talk to increase with frequency but it is not always a monotonic increase. In a narrow window around a delay of about 10 μsec, the value of F is low for all frequencies. This would be the preferred range of delays for this print-head and ink. Note also, that the maximum delay for any frequency is one half the period of that frequency. This puts a limit on the only other possible window at about 24 μsec.

Experimental tests of actual cross-talk reduction made with a similar print-head confirmed that significant reductions in cross-talk could be achieved by operating with delays in the vicinity of the 10 μsec minimum.

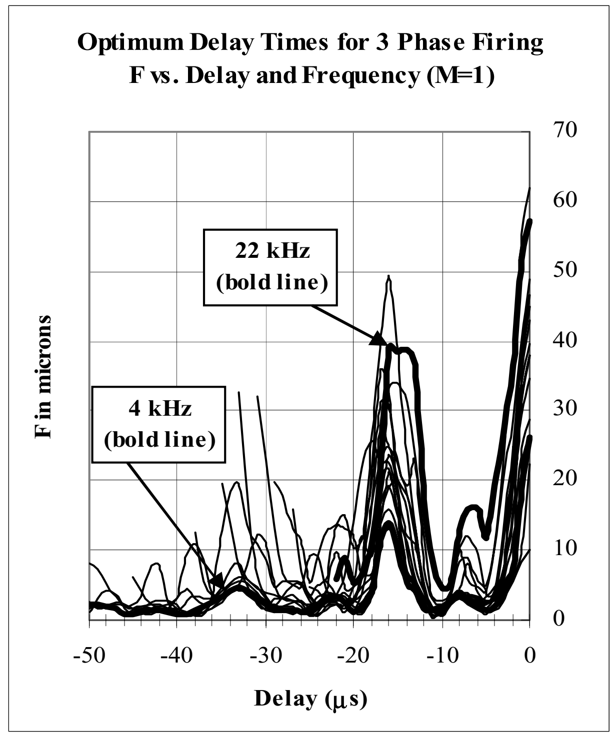

Figure 3. Figure of demerit for three phase firing over a frequency range from 4 to 22 kHz.

V Conclusion and Future Development

Cross-talk in a drop-on-demand ink jet can be significantly reduced by interlacing two or three groups of channels each group having a short delay in the firing time with respect to other group(s). This is a new approach and differs from a previous interlaced delayed firing scheme because the delays are calculated to be short and to maximize the "destructive interference" of the "cross-talk wave" contributions from each channel.

For both the two phase and three phase (equal delay) cases, there are optimum delay times at close to 0.5, 1.5, 2.5 etc. times the period of a fundamental chamber resonance of the print-head used. The window around the shorter delay time is clearly preferred for the two phase case because there is better cross-talk cancellation. Also the shorter delay may obviate the need to use an orifice plate with shifted orifice locations to compensate for the delay and can potentially be used at higher frequencies. For the three phase case at low frequency, the windows at 1.5 and 2.5 times the chamber period are a little lower than the 0.5 period window. The 0.5 period window shows less cross-talk suppression than in the two phase case but may be a little wider. When frequencies up to 22 kHz are considered, the 0.5 period window is clearly better.

There are not yet sufficient data to show the overall trend in going to higher numbers of phases. It may be that the windows tend to become wider but, as yet, this is only a guess. The full analysis of higher numbers of phases with unequal delays and at high frequencies will require computational methods for optimizing a multi-variable function. Other areas for future development include assessing the sensitivity of the method to print-heads having multiple internal resonant frequencies with different degrees of coupling and damping.

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Biographies

Stuart Howkins received his B.Sc and M.Sc in physics from Imperial College and Chelsea College of Science and Technology, London University and, in 1963, a Ph.D. in physics also from Imperial College. Since 1979 he has worked in a research/advanced technology group started by Exxon, later acquired by DataProducts Inc. and now Hitachi Printing Solutions America, Inc. This work has been primarily on the development of the company's proprietary piezo-electric rod expander ink jet print-head. His name appears on 12 US ink jet patents and he is a member of IS&T.

Charles Willus received his B.M.E. degree from Cornell University in 1965 and a Ph.D. in Mechanical Engineering from The California Institute of Technology in 1971. Since 1988 he has worked in Advanced Technology for Hitachi Printing Solutions America, Inc., in Connecticut. His work has primarily focused on developing, adapting and applying mathematical models for development and design of ink jet print-heads. His name appears on 6 US patents and he is a member of the IS&T and the ASME.

Hiroshi Nishimura received his B.Sc in Natural Resource Development from Hokkaido University in 1982. Since then he has worked in engineering for Hitachi Koki Co., Ltd. in Japan. In 1991 he joined an inkjet group of Hitachi Printing Solutions America, Inc. (then Dataproducts Corporation). His work has been primarily on the development of the company's proprietary ink jet heads and peripheral systems. His name appears on 3 US patents and several Japanese patents. He is a member of IS&T.