

Effect of Parameter Variations on Drop Placement in an Electrostatic Ink Jet Printer

Abstract: This paper discusses the sensitivity of drop-to-drop spacing in the print plane of an ink jet printer to other printer variables. Two designed experiments, a fractional factorial and a central composite, combined with standard analysis identified the critical variables and provided a mathematical expression useful for setting tolerances.

Introduction

Electrostatic ink jet printers deposit ink drops on a printing surface to form character-like configurations of dots. In these printers, a drop generator produces a stream of uniformly sized and regularly spaced drops. As the drops form, they are either uniquely charged or remain uncharged depending on the character to be printed. The drops pass through an electrostatic field. Charged drops are deflected to print positions on the document, whereas uncharged drops are collected and returned to the ink supply.

Figure 1 shows the ink jet printhead, which consists of the drop generator, charge electrode, deflection plates, and gutter. In addition to components that provide these basic printer functions, the figure also shows a charged drop sensor that is used in maintaining character height and charge synchronization [1].

The quality of the printed character depends primarily on the relative positions of dots on the document. Dot placement is largely controlled by limiting the tolerances of the printhead variables, provided the nominal printer configuration accurately places the ink drops. Of interest, then, to both the development and manufacturing engineer are the allowable ranges of the printhead variables that will maintain adequate print quality.

This paper discusses the sensitivity of drop-to-drop spacing in the print plane to other printer variables and establishes guidelines for setting the tolerances of the variables to limit dot spacing errors. The variables considered in the study (shown symbolically in Fig. 1) are identified in the Appendix.

The study was divided into two phases. In the first phase, a two-level fractional factorial experiment established the relative importance of the variables to drop placement. Each of the significant variables was varied in turn on an operating printer in which component tol-

erances were closely controlled (hereafter called the prototype printer), and the resultant print quality was observed. From a comparison of these two groups of results, a subset of the most significant variables was defined.

Figure 1 Electrostatic ink jet printhead and variables that affect drop placement.

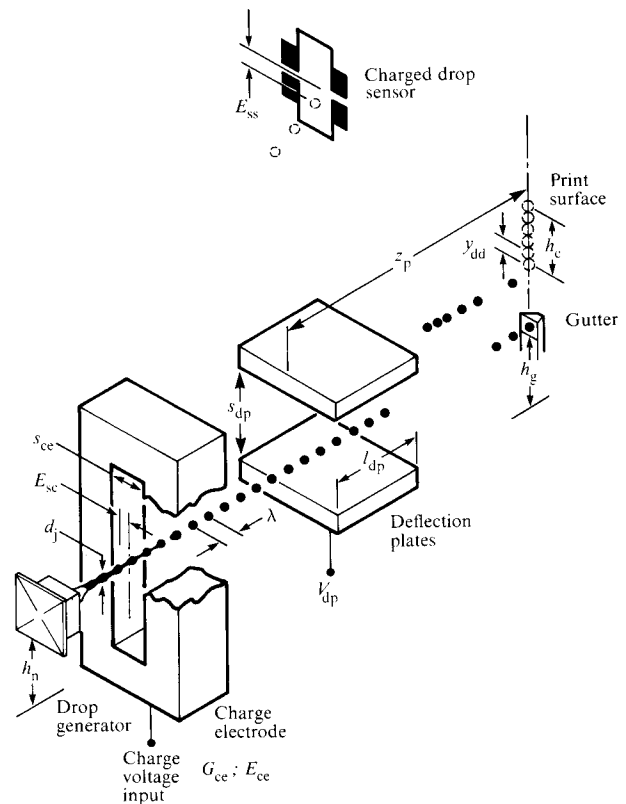


Table 1 Fractional factorial experiment: variables, levels, and summary of results.

Experimental variables	Standard notation	Percent change from nominal	Relative influence of variables on drop-to-drop spacing															
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
d_j	A	-1.5			2			1	2	4	1	2	3	4	1		4	1
s_{ce}	B	8.0	7	6	2		2	1	2		1			2	1		1	
s_{dp}	C	3.0	1			2	3	3	1	4		2	1	1	3	1		3
l_{dp}	D	-0.4	1			1		3	2		1	1	1	1	5	1	4	4
h_n	E	5.0			2		1	1	1	1	1	2	3		2	2	5	4
h_g	ACD	-14.0				2			1	1	1	2	3	3	1	4	2	2
z_{p1}	CDE	-1.9		2	2	3	4	1	1			3	2		2	1	1	3
E_{sc}	ABC	8.0	2	4	5	2	3		2		1		2	1		1	2	
V_{dp1}	BCD	-1.0				4	4	3			1	1	2		2	3	1	1
λ	BDE	-1.6				1		2	2	2	5	3	2	1	1	3	2	1
h_c	ABCDE	1.2	1	2		1		2	1	1	4	1	2	2	2	2	2	2
V_{dp2}	ABE	-2.0				1	1	1	4	5	2	3	4		2	1	1	
G_{ce}	ACE	2.0			7	3	2	3	1				1	4				3
E_{ss}	ADE	1.4	3	7	2	1	1	2	2	1	2				1	3		
z_{p2}	ABD	-1.9	1		2	2	3	1	2	2	3	1	1	3	1	2		1
E_{ce}	BCD	± 0.30	9	4	1	2	1		1	3	1	2		1				

In the second phase of the study, a central composite experiment led to a mathematical expression that related drop-to-drop spacing to the remaining subset of variables. The variance of this expression was then used to establish the tolerance guidelines.

The next two sections describe the design of the two experiments and give the important results obtained in each phase of the investigation. Much of the supporting background information necessary for a fuller understanding of the study is left to the discussion section.

Fractional factorial experiment

The first phase of the study identified those variables having the greatest effect on drop placement. The primary experiment in this screening procedure was a thirty-two trial, two-level fractional factorial experiment [2] in sixteen variables. The variables of the experiment are shown in Table 1. (The standard designed-experiment symbols in the second column of this table can be used to construct the design matrix of the experiment.)

In the experiment, one level of each variable was set equal to the corresponding value in the prototype printer. The other levels were obtained by changing the nominal values by the percentages shown in Table 1. The magnitude of these changes reflected initial estimates of the required tolerances to maintain accurate drop placement.

Three representative drop patterns from ink jet characters were selected for this phase of the study. One pattern consisted of a long continuous drop segment. The second and third pattern each consisted of two short drop segments separated by blank spaces. Once the test

equipment was arranged for a particular trial, the deflection heights were measured for each drop in the three patterns. The resultant spacings between adjacent drops in the patterns (a total of twenty-five) were taken as the responses of a trial.

The relative influence of the experiment variables on each drop-to-drop spacing, the variable effect, was determined by calculating the change in average response for the two levels of each variable (the standard Yates analysis). Summarized results of this analysis are given in the remaining columns of Table 1. In these columns, the variable effects are ranked by magnitude with a column heading of 1 corresponding to the effect of greatest magnitude. The numbers within the columns indicate the frequency of occurrence of the variable effects at a given rank level.

Over the variable ranges considered, this experiment showed that charge voltage errors and charge voltage drift have a strong influence on drop-to-drop spacing. Charge electrode plate spacing, the amount of error in stream centering, and the error in null position of the charged drop sensor appeared to be of equal importance. The initial value of deflection voltage, the deflection plate spacing, and the paper plane location had a lesser influence.

These variables, with relatively large to more moderate effects on drop placement, were varied on the prototype printer to confirm their effects in a greater variety of drop patterns. Print samples were obtained with each variable, in turn, set to extreme tolerance values. Taken together, the fractional factorial and print results demonstrated that s_{ce} , E_{ce} , E_{sc} , and to a lesser extent G_{ce}

Table 2 Ranges of drop-to-drop spacing for various combinations of variable tolerances.

Variables	$\pm 3\sigma$ tolerance ranges as percent of nominal values							
	nominal printer				s_{ce} increased 12%			
s_{ce}	$\pm 5\%$	$\pm 5\%$	$\pm 2\%$	$\pm 2\%$	$\pm 5\%$	$\pm 5\%$	$\pm 2\%$	$\pm 2\%$
E_{sc}	$\pm 5\%$	$\pm 5\%$	$\pm 5\%$	$\pm 2\%$	$\pm 5\%$	$\pm 5\%$	$\pm 5\%$	$\pm 2\%$
G_{ce}	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$
E_{ce}	$\pm 0.5\%$	$\pm 0.25\%$	$\pm 0.5\%$	$\pm 0.25\%$	$\pm 0.5\%$	$\pm 0.25\%$	$\pm 0.5\%$	$\pm 0.25\%$
E_{ss}	$\pm 1.5\%$	$\pm 1.5\%$	$\pm 1.5\%$	$\pm 1.5\%$	$\pm 1.5\%$	$\pm 1.5\%$	$\pm 1.5\%$	$\pm 1.5\%$
$\pm 3\sigma_y$	$\pm 38\%$	$\pm 32\%$	$\pm 27\%$	$\pm 18\%$	$\pm 25\%$	$\pm 14\%$	$\pm 24\%$	$\pm 13\%$

and E_{ss} , were important variables affecting drop placement. Thus we decided to further investigate the influence of these variables and to establish the necessary tolerance guidelines.

Central composite experiment

A mathematical expression that relates drop-to-drop spacing to the five most important variables was developed in the second phase of the study. We used this expression to evaluate the effect of various combinations of variable tolerances on drop spacing.

Again, the approach in the second phase of the study was primarily experimental. A central composite experiment [3] (arranged in a sixteen-trial fractional factorial portion, six trials at nominal conditions and ten axial-point trials) was selected for this phase of the study. The experiment provided enough information to generate a linear second-order prediction equation that relates drop-to-drop spacing to the five variables of interest. The levels of the variables in the experiment were as follows: 1) nominal printer values in the six trials representing nominal conditions; 2) ± 8 , ± 10 , ± 3 , ± 0.53 , and ± 1.9 percent changes, respectively, to nominal values of s_{ce} , E_{sc} , G_{ce} , E_{ce} , and E_{ss} in the fractional factorial portion; 3) twice the percentage changes of the fractional factorial trials in the axial-point trials.

With two exceptions, the composite experiment and fractional factorial experiment were conducted in the same manner (that is, test patterns were deflected and the resultant drop-to-drop spacings defined as the results of the trials). The test pattern for the composite experiment was changed to a merged pair followed by a single drop, with this pattern being deflected to three successively higher print positions. This change was made because the results of the fractional factorial experiment showed that the positions of drops in short segments were more easily disturbed by variable changes than drops in long segments. Further, a single charge voltage error value was applied in turn to the voltages for each drop in this pattern. Thus, a total of nine pairs of posi-

tions were recorded for each trial in the fractional factorial portion of the experiment and for the two axial trials involving charge error.

Once the total set of measured responses was available, the coefficients for the quadratic models were determined by solving the normal equations of the experiment. Nine sets of coefficients were calculated, one for each charge error condition in the three pattern locations described above. Two notable features of the coefficient arrays were evident: 1) In the three sets of coefficients for a given pattern location, the magnitudes of the significant coefficients were very nearly equal in value and did not depend on the drop in the segment perturbed by voltage errors. The one exception to this trend was the charge voltage error coefficient. This coefficient had a relatively small constant value for all deflection heights for those cases in which voltage error was applied to the second drop in a merged pair. This implies that voltage errors on the second drop of a merged pair had much less influence on the impact location of the merged pair than an equal error on the first drop of the pair. 2) The significant coefficients of the prediction equation increased in magnitude as the test pattern moved to progressively higher deflections. Many coefficients increased by nearly an order of magnitude as the drop segment moved from the lowest to the highest position. The most restrictive requirements for variable tolerances, therefore, came from the prediction equations for drops at the highest deflection positions.

Based on these two observations, the results for the case with voltage errors applied to the first drop in the highest deflected pattern were used to develop the prediction equation,

$$y'_{dd} = -5.798 s'_{ce} + 0.2436 E_{sc} + 2.928 G_{ce} - 47.22 E_{ce} + 0.8983 E_{ss} + 0.220 (s'_{ce})^2 + 0.2049 (E_{sc})^2 + 0.5905 (E_{ss})^2, \quad (1)$$

where the primed variables indicate percentage changes from nominal values.

The variance of this equation [4] can be used to evaluate variable tolerances in terms of the resultant range in drop-to-drop spacing, y'_{dd} . If we assume that the variable tolerances correspond to the $\pm 3\sigma$ points of the variable distributions, then Table 2 gives some tolerance combinations of interest and the resultant 3σ range of y'_{dd} for both the prototype printer and the case with s_{ce} set to a value larger than nominal.

Discussion

The printer discussed in this paper provides a unique charging voltage for each drop in every drop pattern of interest. (These unique voltages give the proper balance among the geometry-dependent electrostatic and aerodynamic forces that affect the drop trajectories.) The drops in characters to be printed must be identified in terms of these patterns, and the appropriate voltages to charge the drops are selected from a stored data base. Drop placement accuracy in a particular printer, then, depends largely on how closely its printhead components match the prototype components used in measuring the charge voltage data set.

In this paper we have evaluated variable tolerances in terms of drop-to-drop spacing. The following subsections provide background information for the primary experiments used in the investigation.

• Experiment organization

The experiments in this investigation included many of the variables important to drop placement and were structured to account for all phases of printer life. For example, as a printer progresses from a collection of parts on an assembly line to operation in an office environment, its evolution can be divided into three significant stages. The first stage is the final printhead assembly, in which some combination of the variables d_j , s_{ce} , s_{dp} , l_{dp} , and z_{p1} exist. The variables h_n and h_g also belong to this stage and account for situations where the stream is not parallel to the surface of the deflection plates.

The second stage of printer evolution can be defined as the collection of adjustments that is required to place the machine in operation. For example, the stream is centered in the charge electrode (with some amount of error, E_{ce}), and the ink supply pressure is regulated to set λ . Next, the deflection voltage supply is energized. Its initial value is V_{dp1} . Characters are printed and the gain of the charge electrode driver is adjusted to set the character height to h_c . The printer is now ready to be placed in service.

After some period of service, the variable values may drift; this is the third stage of printer evolution. Since the printer runs unattended after the initial adjustments, a means is provided in the printer (the charged-drop sensor and pressure adjusting system) to account for

many of these changes. For example, the deflection voltage may change to V_{dp2} , and the gain of the charge electrode drive may drift (changing G_{ce}). For changes in these two variables, however, the charged drop sensor detects the change in position of a charged reference stream of drops and initiates a change in the source stream velocity (via a pump servo cycle) to return the reference stream to the null location of the sensor. However, the sensor cannot predict precisely its own null condition, and some error in the null location of the reference stream, E_{ss} , will occur.

On the other hand, some changes in the third stage may not be detected or corrected by the charged-drop sensor servo system. Two examples were included in the experiments. The distance to the print plane, z_{p1} , may change to z_{p2} due to eccentricities in the paper drum or a nonparallel relationship between the axis of the drum and the direction of printhead motion. Also, errors E_{ce} induced or superimposed on the charge voltage data set may be present but go undetected by the charged-drop sensor. (Of the fourteen variables identified symbolically in Fig. 1, two variables have been entered twice and given an additional subscript of 1 or 2 in Table 1. The repeated variables, which account for possible changes in values, are separated in the time sequence of events by a manual adjustment or machine response and can be adjusted independently.)

• Drop patterns

The drop patterns selected for the fractional factorial portion of the investigation were chosen to represent the two possible extremes in the types of ink jet character drop segments. In an operating printer, both individual drops and merged pairs of drops strike the paper. Under ideal conditions, the printer deflects single drops in ascending order to uniformly separated heights or matrix positions. The resultant column arrangement of dots and blanks is called a scan. Merged pairs always begin a scan and are placed between the matrix positions defined for single drops. For scans consisting of a forty-position column of drops and/or blanks, 2^{40} drop patterns are possible. One is a scan consisting of a 40-drop segment with no blanks, and the other extreme is one drop placed somewhere among the forty print positions (a totally blank scan is not of interest). A ten-drop long segment was selected for the experiment because it was believed to adequately represent one extreme in the drop patterns. The remaining two patterns, consisting of short segments, represented the other extreme.

The distances between adjacent drops in the patterns were the results of the experiments. The absolute deflection heights were of less interest, because print is considered acceptable if all drops are shifted vertically by the same amount. Further, drops are rarely deflected to

adjoining scan locations so no attempt was made to record this type of drop misplacement.

The voltages for the printed drops in the test pattern were measured ten times with the prototype printer. The average values of these drop voltages were used in all trials to deflect the drops; they thus simulated the data set stored in an operating machine.

- *Variable levels*

The off-nominal variable levels in the fractional factorial experiment reflected initial estimates of the variable ranges that were needed to maintain accurate drop placement (measured in terms of drop-to-drop spacing).

The change in E_{ce} varied within ± 0.3 percent of a reference value for the following reason: At the onset of the experiment we were not sure of the magnitudes and combinations of voltage error that would yield the worst case. Therefore, a fixed sequence of random voltages that varied within ± 0.3 percent of the reference value was generated. Each term in the sequence was paired with one voltage value in the fixed data set; the two values were added in those trials requiring charge voltage errors.

The variable levels in the composite experiment were chosen so that the resultant model could be interpolated inside the variable ranges.

- *Experimental apparatus*

The laboratory apparatus directly modeled all variables associated with component dimensions, distances between components, and voltage settings; however, a physical print surface was eliminated. For greater measurement accuracy, the heights of the deflected drops above the source stream were measured in a plane located in the position normally occupied by the print surface. Further, the feedback system responses were simulated without a charged drop sensor by noting the reference stream location in this plane and manipulating its position through manual ink supply pressure adjustments.

- *Experimental results*

Over the variable ranges considered, the fractional factorial experiment showed that four variables affecting drop charge values, s_{ce} and E_{sc} , which contribute to the stream-to-charge electrode capacitance and inter-drop capacitance; and G_{ce} and E_{ce} , which directly influence the stored data set, had a strong influence on drop-to-drop spacing. These results were somewhat expected since the proper operation of the printer is based on charge adjustment. More noteworthy, however, is that errors in charging voltages of only 0.3 percent of the maximum reference value showed high significance.

The performance of the charged-drop sensor in the velocity adjustment system also showed large calculated effects. Any stream velocity adjustments have an effect on charging capacitance and influence the electrostatic and aerodynamic forces acting on the charged drops.

The effects of deflection voltage and deflection plate spacing, which are corrected by either the initial charge electrode gain setting or the velocity control system, are somewhat secondary in importance. The distances to the paper plane, both initial and drifted, also have secondary effects. Changes in paper plane distance vary the drop intercept time. The effect of z_{p1} is corrected by a gain change in the data set to correct character height, whereas z_{p2} variations give rise to uniform character expansions or contractions. The initial setting of character height is another secondary effect, about which more is said later. Finally, the printhead variables d_j , l_{dp} , h_n , and h_g and the setting of λ show the smallest effects.

The composite experiment results provided the predictive model for revising variable tolerances.

By taking the variance of Eq. (1), we can see the effect of various combinations of variable tolerances on drop spacing. Table 2 gives four tolerance combinations for both the nominal prototype printer arrangement and the prototype printer with s_{ce} increased 12 percent. An increase in s_{ce} over the nominal values serves to make drop-to-drop spacing less sensitive to variable tolerances in the printer. A comparison of y_{dd} ranges for the similar tolerance situations in Table 2 shows a decrease in this range for all cases in which s_{ce} was increased 12 percent.

We attempted to keep y_{dd} variations below ± 15 percent, and Table 2 shows some of the tolerance situations used to accomplish this. There are many possible tolerance combinations, however, and the group of tolerances finally selected must be based on the economics of the problem as well as on manufacturing capabilities. An expression such as Eq. (1) can be used to study the vast number of possible trade-offs.

Obviously, a study of the type described in this paper cannot account for all variables that may influence drop-to-drop spacing. For example, we showed that h_c , the initial setting of character height, becomes more important than indicated in the fractional factorial experiment when wide ranges of printhead temperatures are considered and the nominal s_{ce} value is used. When s_{ce} is increased to a value above nominal, however, the effect of h_c again becomes secondary in importance, even in the presence of wide temperature variations.

Summary

For the electrostatic ink jet printer considered in this paper, a designed experiment investigation has produced tolerance guidelines that are useful for ensuring accurate drop placement.

Beginning with sixteen variables, each with proposed tolerance ranges, the first experiment identified five variables that had a strong influence on drop-to-drop spacing. A second experiment provided a simple mathematical expression between these variables and drop-to-drop spacing that could be used to revise the original tolerance estimates.

Finally, the second experiment indicated a need to increase the charge electrode width, which proved to be important for ensuring quality printing over wide temperature ranges.

Appendix: Glossary

d_j	ink jet diameter
E_{ce}	charge voltage error as a percent of maximum charging voltage for single drop
E_{sc}	stream centering error as a percent of nominal s_{ce}
E_{ss}	stream sensor null error as a percent of maximum deflection
G_{ce}	gain setting of charge voltage data set
h_c	height of printed character
h_g	height of gutter above datum
h_n	height of nozzle above datum
l_{dp}	deflection plate length
s_{ce}	charge electrode spacing
s_{dp}	deflection plate spacing
V_{dp}	deflection plate voltage

y_{dd}	drop-to-drop spacing in paper plane
z_p	distance to paper plane from entrance of deflection plates
λ	drop-to-drop spacing in stream
'	Prime as a superscript on a symbol indicates a change in that variable from its nominal value.

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