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Splatter During Ink Jet Printing

Abstract: When an ink drop traveling at relatively high velocity impinges on a flat surface such as paper, part of the drop breaks up into many very small droplets that are deposited at other points. If these droplets are relatively large, then visible splatter results. Various parameters (ink properties, drop velocity, drop volume, space between drops, etc.) are investigated to determine their effect upon splatter and hence print quality. Print samples were made while varying these parameters, and the resulting print quality was assessed. A simple relationship among the kinetic energy of the drops, the overlap between drops, and print quality based upon splatter is developed. This relationship can be used to establish design boundaries in an ink jet printer.

Introduction

In an ink jet printer, a stream of uniformly sized drops is directed towards a recording medium (paper). The drops are deflected so as to be deposited on the paper in suitable patterns to form characters. Print quality is dependent upon such factors as drop placement accuracy, ink spot size and spacing (resolution), and ink splatter. Those factors that influence drop placement accuracy, such as aerodynamics, charge interaction [1], etc., have been examined; also, factors influencing spot size, including nozzle diameter, drop wavelength (drop spacing), and ink and paper properties, have been studied. However, ink splatter does not readily lend itself to mathematical prediction, and this study was conducted to determine experimentally those factors related to ink splatter.

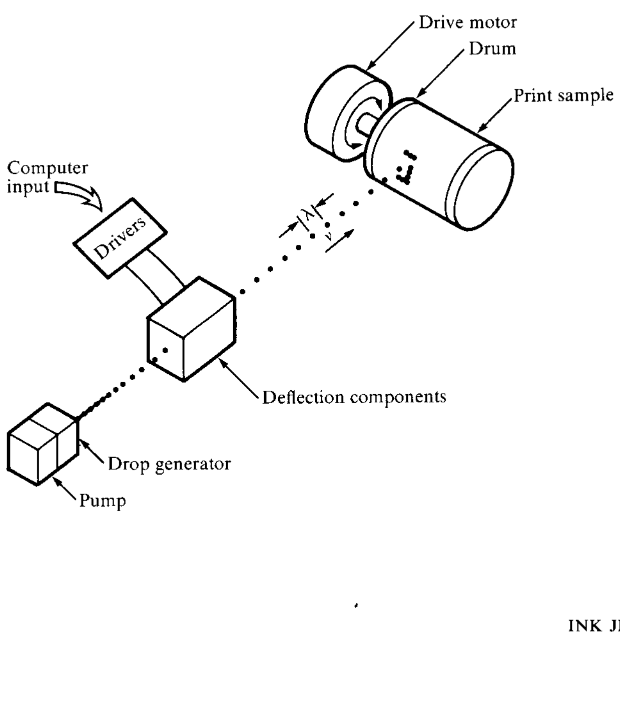
Under certain conditions, parts of an ink drop upon impact with the paper are broken off from the main drop, forming much smaller droplets [2]. These droplets are redeposited on the paper, usually in the vicinity of the main drop. This splatter causes the printed characters to look fuzzy and, in severe cases, even masks them. Some splatter can occur without significantly affecting print quality, since the human eye cannot readily detect spots smaller than about 0.025 mm (0.001 in.) [3]. Thus, by looking at the printed characters, one can judge subjectively whether the degree of splatter is detrimental to print quality.

The amount of splatter is related to various factors, such as drop size, impact velocity, etc. Here we define the key parameters relating to splatter and set limits on them such that an unacceptable amount of splatter will not occur. An experimental procedure is followed in which the key parameters are varied and the relationship of those parameters to splatter is obtained. Once these design limits are established, an acceptable operating region for an ink jet printer based upon splatter considerations can be established.

Experimental procedure

The printing system used for this study consists of a small drum robot printer (Fig. 1) controlled by a computer. A pump pressurizes an ink chamber causing an ink jet to emanate from a nozzle. The jet is broken into uniformly sized drops by the drop generator, and the drop trajectories are modified in predetermined patterns by the drop deflection components. Drop columns of equal height form character rasters. Those drops not needed to form characters are deflected away from the paper into a stationary receptacle (or gutter). In addition, within printed portions of characters, only every other drop is used. This ensures better drop placement because of more favorable aerodynamic [4] and drop interaction conditions.

Figure 1 Experimental setup.



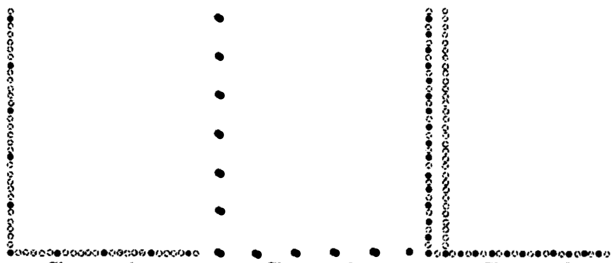


Figure 2 Some of the characters used.

Based on study of previous experimental results and high-speed moving pictures, we concluded that the factors that should be varied in the study of splatter are drop size (spot size), drop velocity, spot spacing (resolution) on the paper, time between successive drop impacts, and, to some extent, ink properties.

Drop size is influenced by two controllable factors: nozzle diameter and drop wavelength. The relationship [5] among drop wavelength, drop velocity, and drop generation frequency is

$$v = f\lambda, \qquad (1)$$

where v is drop velocity (cm/s), f is drop generation frequency (drops/s), and λ is drop wavelength (cm). Thus, for a given velocity, wavelength is changed by varying drop generation frequency. Wavelengths between 0.020 cm and 0.045 cm were used.

Basically velocity is varied by changing pump pressure. The velocity range chosen was from 6.98 m/s to 18 m/s. The tangential drum velocity is approximately 20 cm/s. At this low drum velocity the angle of impact between the ink stream and tangential drum velocity is not significant. Spot spacing on the paper is determined by the drop pattern selected for different characters, the maximum deflection of the raster, and the drum speed. Five character patterns, all in the form of the capital letter L, were chosen, with each pattern using more of the available drops in the raster. Three of these characters are shown schematically in Fig. 2.

A maximum of 32 drops per vertical scan and 26 scans per raster determine the total number of drops available per character. However, as seen in Fig. 2, the character 1 uses the lowest number of available drops in its scan, as well as the lowest number of available scans in its raster; only every sixth drop in the scan and only every sixth scan in the raster are used. For the character 1, then, a total of five drops comprises the horizontal leg of the letter L and a total of six drops comprises the vertical leg of the letter L. Successive characters use more drops per scan and more of the available scans in the raster, with the last character, 5, using the most drops—every other drop and every other vertical scan.

The maximum deflection of the raster is set such that there is a small space (about one-half ink spot diameter) between successive ink spots of the vertical leg of the letter L for the least dense character, 1. This maximum is then fixed such that the remaining characters have the same maximum deflection. Thus, the vertical spacing between the spots for all the characters can be determined once the spacing between the spots for the character 1 has been measured (by means of a high-powered microscope). Since the raster heights are the same, the spot spacing for each character can be calculated:

$$H = S_n = \tfrac{1}{6}S_1, \text{ or } S = \tfrac{1}{6}S_1/n, \qquad (2)$$

where S is the spacing (in cm) between spots for the character, S_1 is the measured spacing (in cm) between spots for the character 1, n is the fraction of the drops in a scan used to generate the character, H is raster height, and $\frac{1}{6}$ is the fraction of the drops in a scan used to generate the character 1.

This method avoids the problem of measuring the space between spots that are extensively overlapped and therefore not distinguishable. Drum speed also influences the spaces between the spots of the horizontal bar of the L. Drum speed is adjusted such that there is a small space between successive spots of the horizontal leg of the least dense character, the character 1. The horizontal spacing between drops for the remaining characters is determined using (2), with the drum speed kept constant. The choice of characters also allows for a variable amount of time between successive drop placements on the paper. For example, for the vertical leg in the character 5, the densest character, the time between two successive drops placed on the paper is

$$T = 2/f,$$

where T is the time between two successive drops. For the horizontal leg of the character 5, the time between two successive drops hitting the paper is

$$T = 2\,N/f,$$

where N is the number of drops per scan. We felt that this time between two successive drops impinging on the paper might be important because of the time taken by the first drop of the pair to spread. That is, the second drop could impact either the paper or the ink of the first spot, depending on the time between impacts and how rapidly the first ink drop spread.

A print sample, which is generated for each different set of conditions, usually consists of four lines. Each line contains a set of five of each of the five characters. See Fig. 3. The operating conditions that can be varied for each print sample are: stream velocity, drop frequency (wavelength), nozzle diameter, and ink composition.

The stream velocity is measured by lighting the ink drop stroboscopically and measuring the space between drops with a high-powered microscope. Equation (1) is then used to obtain drop velocity. Spot spacing is measured as described above using Eq. (2). Spot size for a given print sample is measured using a high-powered microscope and taking an average of the spot sizes measured. A typical print sample is shown in Fig. 3. The ink used in these studies is a particulate ink. Two different samples of this ink were prepared and used. One sample had a viscosity of 0.0038 Pa · s taken at a shear rate of 1900 s^{-1} and a surface tension of 28.4×10^{-7} N/m. The second sample used had approximately the same surface tension but with a viscosity of 0.0126 Pa · s (at a shear rate of 1900 s^{-1}). The paper used in this study is Moore Business Form 9512 T, a paper typically used for computer output.

The effect of splatter on print quality was determined subjectively, which, although somewhat inefficient, has been shown to be effective [6]. A standard form generated using an ink jet printer was subjectively rated by qualified people, who found it not to have an objectionable amount of splatter. A representative line from each print sample generated for the splatter test was compared to this standard form. The set of characters in this line having the largest spot spacing that contained as much or more splatter than the standard form was identified subjectively. The spot spacing as well as the spot size for this set of characters on each print sample was determined. This set of characters corresponded to an amount of splatter that was on the borderline of being objectionable for the operating conditions relating to the particular print sample. The relationship between the various operating conditions and objectionable splatter is described in the following section. An example is shown in Fig. 3(b) of two sets of characters on a given line for a given operating condition—one set on the borderline of unacceptability and the second set completely unacceptable.

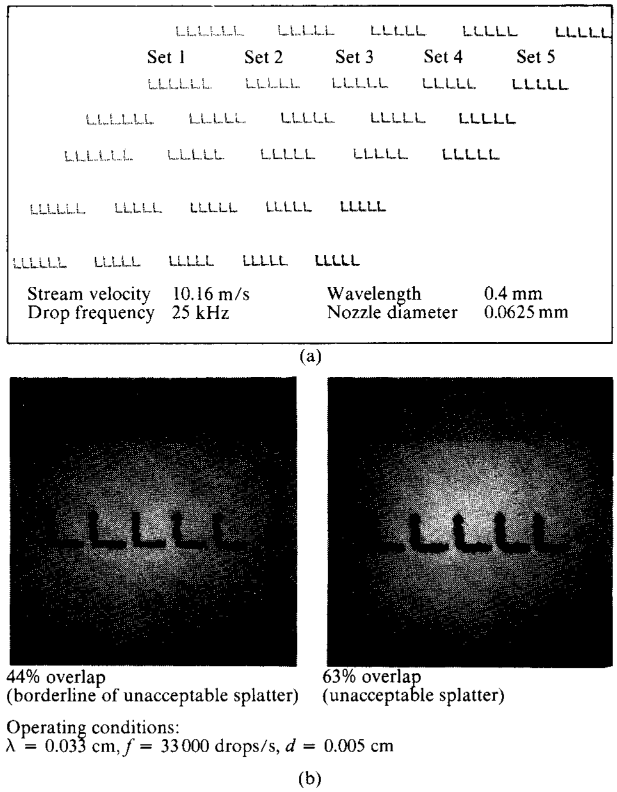


Figure 3 Typical print sample (a) and microscope photographs of a section of a print sample for a given set of operating conditions (b).

Results

High-speed moving pictures show that overlap between successive ink spots is an important factor in the amount of splatter produced. The percent overlap O is

$$O = (D - S)\ 100/D, \tag{3}$$

where D is spot diameter (cm) and S is space between two successive spots (cm).

The drop, having diameter δ, impinges on the paper and spreads to a final ink spot having diameter D. From high-speed moving pictures and from the literature [2, 7], we learned that the velocity at which the ink spreads is approximately 1.6 times the impact velocity. It seems reasonable to conclude that splatter is related to overlap, since the greater the overlap, the greater the volume of ink impacted by the next successive drop, and thus the greater the amount of ink splattered.

In addition, the drop size and the impact velocity have also been shown to be important [2]. With this in mind, we plotted for each print sample the percent overlap corresponding to objectionable splatter as a function of the drop kinetic energy pertaining to that print sample or set of operating conditions. These data are shown in Fig. 4. Other variables, such as drop size, drop velocity, drop momentum, etc., were plotted instead of drop kinetic energy for the given overlap and operating conditions. However, the relationship of Fig. 4 using drop kinetic energy yielded the most consistent results. Since the data appear to fit a hyperbolic curve and because this would lead to a simple design relationship for splatter, we chose a curve approximating the data and having the form

$$O \cdot KE = C_1,$$

where KE is the drop kinetic energy that, for a given

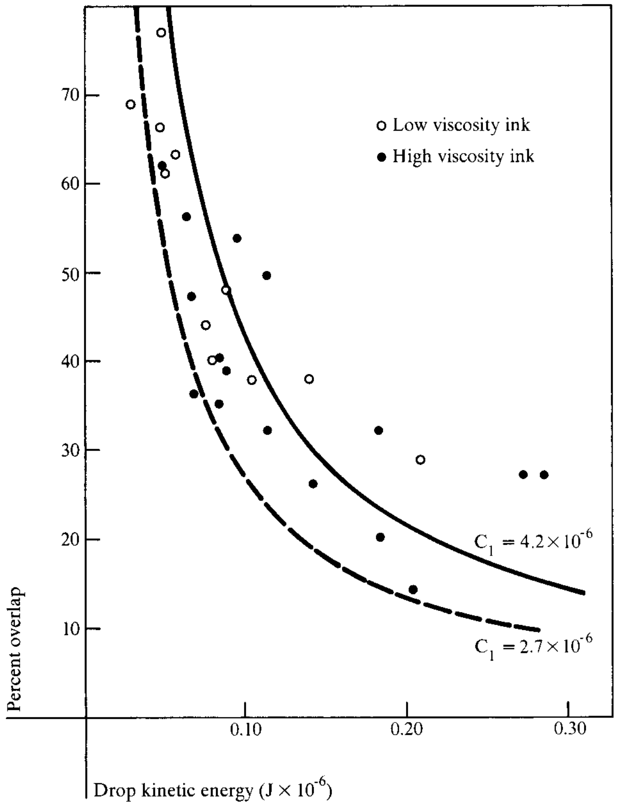


Figure 4 Sample curve.

amount of spot overlap, results in objectionable splatter, and C_1 is a constant obtained from the data. This relationship is plotted as a solid line in Fig. 4.

The value of C_1 is obtained by taking the mean of the products of overlap and kinetic energy for each point (set of operating conditions), i.e.,

$$C_1 = \sum_{i=1}^{M} O_i \, KE_i / M,$$

where M is the number of print samples.

The value of C_1 is 4.2×10^{-6} J. Thus, on the average, for no objectionable splatter to occur, the product of spot overlap and drop kinetic energy must fall below 4.2×10^{-6} J, i.e., the value of C_1. However, because of the scatter in the data, another curve (the dotted curve in Fig. 4) is needed. This curve corresponds to the statement that there is an 85 percent probability that objectionable splatter will not occur if the product of overlap and drop kinetic energy does not exceed 2.7×10^{-6} J.

There are various reasons for the observed scatter in the data. As previously described, five discrete steps are taken in the spot spacing (five character sets) for a given set of conditions. The difference in overlap from one set of characters to the next for a given printing condition is typically about 20 percent. This allows for a possible error in estimating the overlap corresponding to objectionable splatter to be as much as 10 percent overlap. The subjective nature of the objectionable splatter assessment also contributes to this variation. Drop placement errors also act to effectively increase the overlap above that measured. This would then tend to yield more conservative results (prediction of splatter at lower levels) when compared to a printer with either no or fewer drop placement inaccuracies. Typically, drop placement inaccuracy on the drum robot is less than 0.004 cm. This effect would be greatest at the low overlap, high kinetic energy part of the curve.

The time between successive impacts does not seem to be an important factor since there was no discernible difference between splatter on the horizontal and vertical legs of the letter L. This means essentially that the drop spreads faster than the time between successive impacts, which has been verified by high-speed moving pictures. Also, the drying time of the ink is orders of magnitude greater than the time between successive impacts.

Two different inks yield similar splatter results, with drop kinetic energy and spot overlap being the two key parameters. This can be seen from Fig. 4. However, for the same size drop, there was a difference in spot size for the two different inks. The viscous ink yielded a drop size approximately 10-15 percent smaller than that for the less viscous ink.

A design relationship for splatter has thus been established, i.e.,

$$O \cdot KE \leq 2.7 \times 10^{-6} \, J. \tag{4}$$

This relationship must hold if objectionable splatter is to be avoided in single column printing (one column of dots per character stroke), as was done in the generated print samples. However, in multicolumn printing (multiple columns of dots per character stroke) the amount of ink that is overlapped by the drops of the second and subsequent columns, for a given value of spot overlap, is greatly increased compared to one column printing. In multicolumn printing the drops in the second and subsequent columns overlap spots vertically as well as horizontally. Thus, for a given spot overlap in multicolumn printing, a greater volume of ink will be splattered. The acceptable splatter curve of Fig. 4 would be changed for multicolumn printing. For a given overlap in multicolumn printing, a much lower value (probably on the order of 1/2) for drop kinetic energy would be allowed for the objectionable splatter not to occur.

Additional study is required to establish splatter design limits for multicolumn printing. Furthermore, we felt that the effect of different paper types upon splatter would be to change drop overlap for a given set of operating conditions. Thus, paper type would not change the design limits established for splatter. This is another area for further investigation. An example is given in the next section of how Eq. (4) might be used in the design of an ink jet printer.

Design procedure example

We use a simple example to demonstrate how Eq. (4) might be used in establishing the nozzle diameter for a given set of operating conditions. Let us assume that from independent considerations, such as machine throughput, drop placement accuracy, etc., the following operating conditions have been established:

$f = 40000$ drops/s,

$\lambda = 0.030$ cm.

In addition, a spot spacing, S, equivalent to, say, 48 dots/cm is desired in order for the printer to be compatible with other I/O devices.

From print quality considerations, it is desirable to have the maximum amount of spot overlap [3] possible without producing objectionable splatter. In other words, it is desired to obtain the greatest allowable amount of spot overlap for the operating conditions described.

The amount of overlap is directly controlled by nozzle diameter, d, drop wavelength, λ, spot spacing, S, and the amount of spreading of the ink drop once it impacts the paper. In the splatter tests performed and in other previous experiments, it has been shown that the spot size (diameter) typically is linearly related to the nozzle diameter over limited ranges of parameter values, i.e.,

$$D = \alpha\, d, \tag{5}$$

where α is the spread factor. A value for the spread factor over a typical nozzle range and velocity range and for a particular ink and paper type is approximately six.

Since wavelength, λ, spot spacing, S, and spread factor, α, are established, the nozzle diameter can be expressed as a function of the spot overlap. Furthermore, because we know drop frequency, f, and wavelength, λ, the drop kinetic energy can be expressed as a function of the nozzle diameter, d, i.e.,

$$KE = 1/2\ \lambda(\pi\, d^2/4)\rho v^2$$
$$= 1/2\ \lambda^3(\pi\, d^2/4)\rho f^2,$$

where ρ is mass density of ink and v is velocity of ink drop upon impact. Thus, a given amount of overlap corresponds to a particular nozzle diameter, which, in turn, determines the drop kinetic energy. It then must be determined whether the combination of overlap and drop kinetic energy is an allowable one as far as acceptable splatter is concerned.

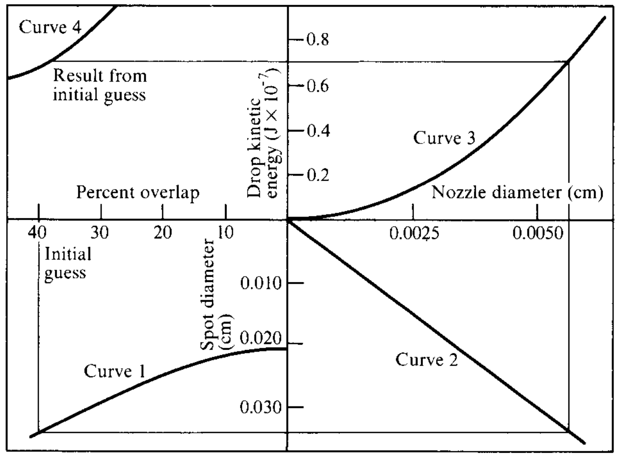


Figure 5 Curves for design procedure.

Figure 5 consists of four graphs. The graph in the lower left corner, curve 1, is a plot of spot diameter as a function of spot overlap for a given spot spacing (Eq. (3)). Curve 2, in the lower right corner, relates the spot size to the nozzle diameter (Eq. (5)). The curve in the upper right hand corner, curve 3, is a plot of the drop kinetic energy as a function of nozzle size (Eq. (6)). Finally, the curve in the upper left corner, curve 4, is the relationship between drop kinetic energy and spot overlap for allowable splatter (Eq. (4)). Any combination of drop kinetic energy and spot overlap that falls above curve 4 corresponds to an unacceptable amount of splatter.

For the conditions chosen, it is desired to determine the maximum allowable spot overlap. An iterative graphical procedure is followed using the four curves of Fig. 5. An initial guess of a 40 percent overlap is made. Using curve 1, this corresponds approximately to a 0.034-cm spot size. This, in turn, utilizing curve 2, corresponds to approximately a 0.0056-cm nozzle diameter. Using curve 3, this nozzle corresponds to a kinetic energy of approximately 0.7×10^{-7} J, which corresponds to a maximum allowable spot overlap of 38 percent. Thus, our initial guess of 40 percent maximum allowable overlap is too high. A new estimate of 39 percent overlap is chosen (midway between our initial guess and final result). This value of overlap, following the procedure described above, is acceptable. The nozzle diameter corresponding to this value of overlap is approximately 0.0055 cm. This then completes the design point for this particular printer, ensuring that objectionable splatter will not occur.

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