Dynamic Simulation of Toner Particle Motion in a TonerJet Printer

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Abstract

A numerical integration method is used to simulate the motion of a group of toner particles under the influence of multiple force fields and elastic collisions as the particles travel from a developer sleeve to a paper surface. Forces and force fields acting on the toner particles are described in equation form and entered into a personal computer application program for integration in selectable time steps. A representative simulation is described using a TonerJet print zone as an example.

Introduction

The motion of toner particles in a typical development zone is influenced by a complex combination of forces, force fields, and elastic collisions. Simple analytical models of individual forces or force fields cannot predict the motion of particles nor the influence of geometry or operating parameters on the particle motion. This report describes a dynamic particle simulation that displays the motion of toner particles using numerical integration methods. A distribution of toner particle sizes is used, each having a charge in proportion to its area. Those particles are placed in a geometric model of the actual print zone having selected elastic properties. The particles are subjected to selected magnetic, electrostatic, and gravitational fields, in addition to electrostatic repulsion, aerodynamic, and elastic collision forces. The motion of individual toner particles is recorded as they move through the print zone to settle on a receptor surface. The general simulation method is described, using the specific geometry, materials, and forces of a TonerJet print zone as an example.

Printing Process

TonerJet[1] is a direct printing process in which charged toner particles are deposited directly onto plain paper. An array of ring electrodes creates dot-sized electrostatic fields to draw charged toner particles through openings in the ring electrodes, depositing the particles in a visible image pattern on a plain paper surface. The simplified TonerJet print zone shown in Fig. 1 uses a monocomponent magnetic toner transported on a developer sleeve that carries the toner into the print zone while charging each particle by contact charge exchange with the developer sleeve material. A uniform electric field is created between a high potential on the back electrode and a low (0 V) potential on the developer sleeve. The uniform field pattern is modified by control potentials on individual ring electrodes in a 2-D control electrode array placed in the print zone. Individual dot-sized electrostatic fields interact with the uniformly charged toner particles, drawing them from the developer sleeve through the apertures in the ring electrodes and depositing them on the paper surface in the desired visible image pattern. The visible toner particle image is then made permanent by heat and pressure fusing the toner particles to the paper surface. Control of the particle motion through the ring electrode apertures by the electrostatic fields is described in a previous report.[2]

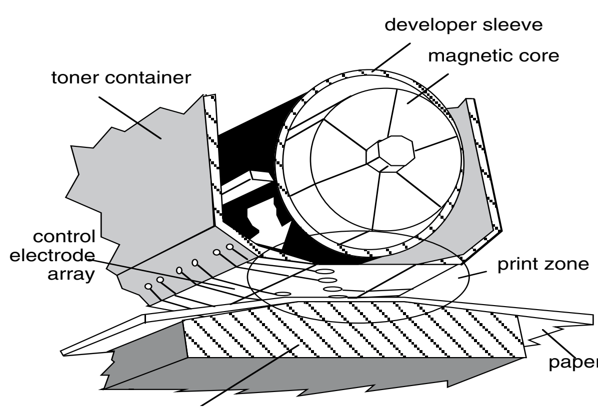

Figure 1. Simplified TonerJet print zone.

Simulation Method

A numerical integration application program[3] is used to describe the motion of toner particles in the TonerJet print zone of Fig. 2. Specific geometry, material properties, forces, and constraints related to TonerJet are entered from experimental and calculated data.

A normal distribution of toner particle sizes centered at a mean value of 6.7 μm is used, based on measurements by the toner manufacturer. Each toner particle has a calculated charge proportional to the square of its diameter, with the proportionality based on the average particle charge and particle diameter. Particles are randomly located in a cubic packing grid on the developer sleeve. Paper of 75 g/m^2 (20-lb basis weight) with a surface roughness of $\pm$5 μm and period of 80 μm is located on the back electrode. Elasticity of the paper is calculated to be 0.39, using the methods of Johnson,[4] and entered as a material property. Surface roughness is included in the geometry of the paper.

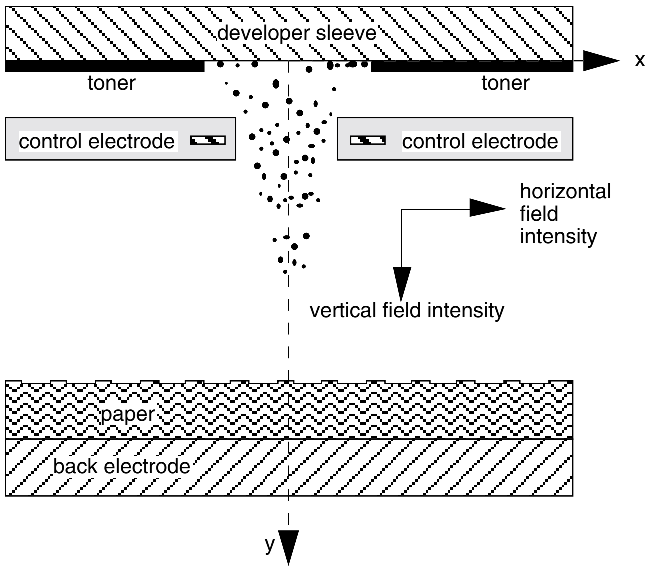

Figure 2. TonerJet print zone geometry.

Forces on Toner Particle

Motion of the toner particles in the print zone is controlled by the summation of several forces on each particle, which includes the following:

Gravitational field, F_g,

$$F_g = -9.81 m_n, \tag{1}$$

where m_n is the mass of particle n.

Electrostatic retention (image) force, F_i,

$$F_i = \frac{1}{4\pi\varepsilon_0}\frac{q_n^2}{(2y_n)^2}, \tag{2}$$

where q_n is the charge on particle n and y_n is its distance from the developer sleeve.

Magnetic retention force, F_m (Ref. 5)

$$F_m = -\left(\frac{\mu-1}{\mu+2}\right) r_n^3 \left[H_x\frac{\partial H_x}{\partial y} + H_y\frac{\partial H_y}{\partial y}\right], \tag{3}$$

where μ is the permeability of the toner particle material, r_n is the radius of particle n, and H_x and H_y are the magnetic field intensities at the center of the developer sleeve magnetic core. The toner particle material is a composite of polymer resin and magnetic oxide particles. The magnetic permeability μ of the composite toner particle material is calculated from the Maxwell relation for magnetic oxide of infinite permeability[6]:

$$\mu = \frac{1+2s}{1-s}, \tag{4}$$

where s is the volume fraction of magnetic oxide in the toner particle. For a 30% volume of oxide in the toner particle material, the magnetic permeability μ of the composite particle is calculated to be 2.3.

Electrostatic repulsion force, F_r,

$$F_r = \frac{q_n}{4\pi\varepsilon_0}\sum_{m=1}^{N-1}\frac{q_m}{(x_n-x_m)^2+(y_n-y_m)^2}. \tag{5}$$

Equation 5 describes the electrostatic repulsion force on particle n as the sum of electrostatic forces from N–1 and other charged particles m, each acting on particle n.

Aerodynamic drag force, F_a,

$$F_a = 6\pi\mu_a v_n r_n, \tag{6}$$

where μ_a is the absolute viscosity of air (0.017 mPa•s) and v_n is the velocity of particle n.

Applied electrostatic field, F_e,

$$F_e = q_n E_n, \tag{7}$$

where E_n is the applied electrostatic field intensity at the position of particle n.

The applied electrostatic fields caused by interaction of the control electrode potential and the back electrode potential are calculated, using a finite difference method. Figure 3 shows the calculated vertical and horizontal field intensities with 1500-V potential between the developer sleeve and the back electrode and the control electrode potential at a low value (–200 V). The vertical field intensity experienced by the toner particle near the developer surface (y = 25 µm) is a very low positive or negative value. Toner particles remain attached to the developer sleeve because the magnetic and electrostatic retention forces are greater than the forces from the dot-sized electrostatic fields.

The field intensity data of Fig. 3 are condensed to closed form equations and entered in the simulation as

$$E_y = 0.82 + \cos\frac{x}{169} + (0.53 + 1.1\times10^{-5}x^2)\tan^{-1}\left(\frac{y-175}{70}\right),$$
$$E_x = \left(\frac{x}{162} - 0.05\right)\exp{-5\times10^{-5}(y-175)^2}, \tag{8}$$

where x and y are in micrometers.

In Fig. 4, the control electrode potential has been raised to +150 V. The vertical field intensity near the developer sleeve surface (y = 25 μm) produces a force on the charged toner particles that exceeds the magnetic and electrostatic retention forces, causing the toner particles to be pulled from the developer sleeve and propelled through the electrode aperture toward the paper.

The field intensity data in Fig. 4 are also condensed to closed form equations and entered into the simulation as

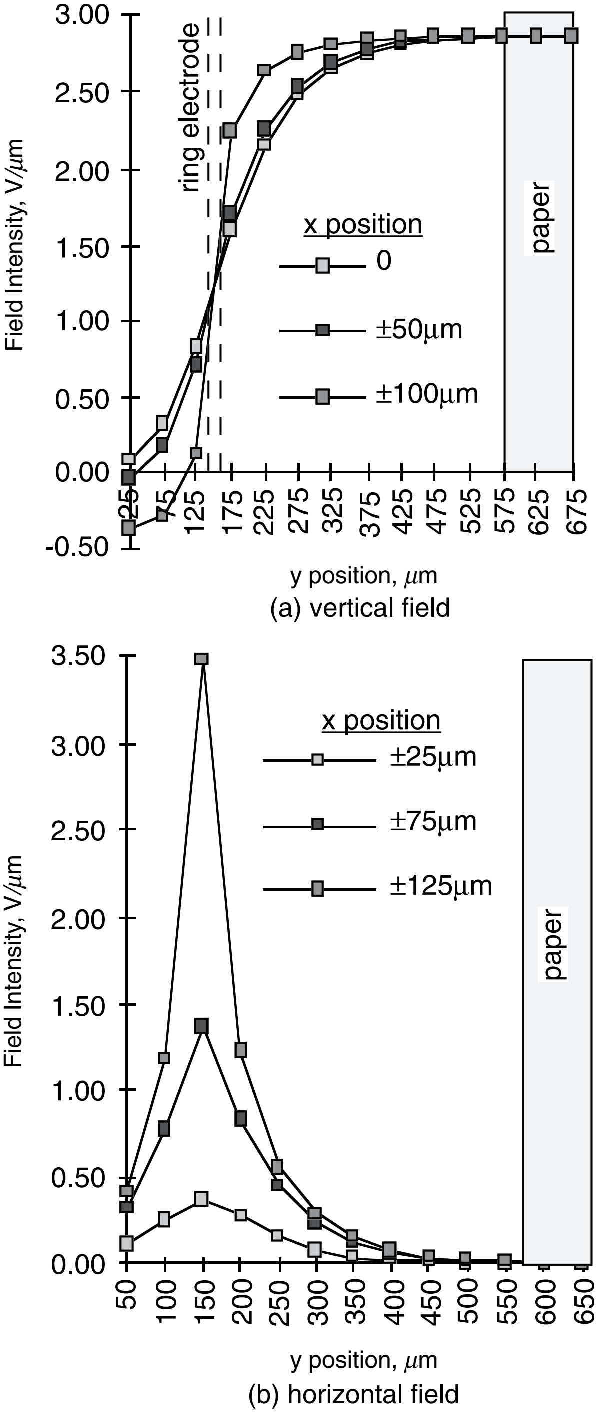

Figure 3. Applied electrostatic field intensities with aperture closed. (a) Vertical field (b) Horizontal field.

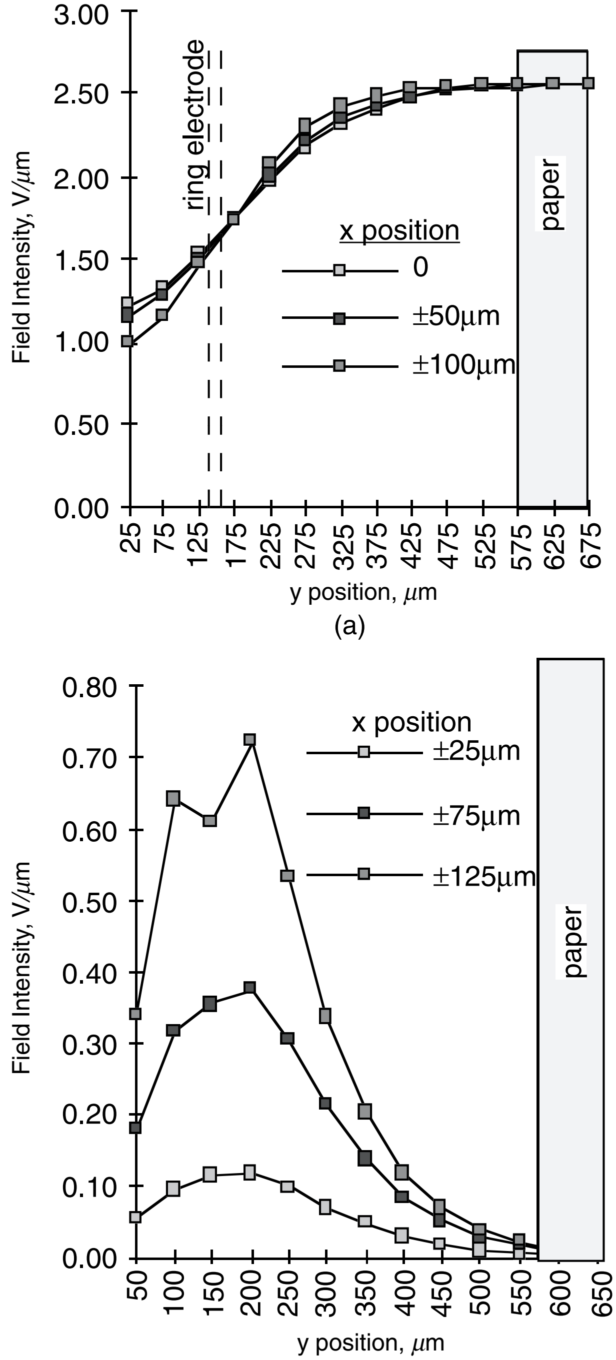

Figure 4. Applied electrostatic field intensities with aperture open. (a) Vertical field (b) Horizontal field.

$$
\begin{aligned}
E_y &= 1.24 - 1.04\tan^{-1}\left(\frac{y-150}{0.4|x|-55}\right),\\
E_x &= \left(0.23e^{0.022|x|}\right)\exp-2\times10^{-4}\left(\frac{y-150}{1.2}\right)^2.
\end{aligned}
\tag{9}
$$

Simulation

Equations 1 through 9 are entered into the simulation where Euler integration of all forces and elastic collisions is performed in selectable steps of 5 μs. The integration calculates a new position for each toner particle as an initial position for the next integration step. The position information for each particle is stored at the end of each integration step for replay in either a continuous run mode or forward and reverse single-frame steps.

The simulation of a single dot begins with the control electrode potential in the print condition (aperture open). using Eq. 9 to describe the applied field intensity. Figure 4(b) shows that there is a strong converging field in the horizontal plane that tends to "focus" the toner particles into a converging trajectory during their flight to the paper, as shown in Fig. 2.

After a selectable time, the control electrode is changed to the nonprint condition (aperture closed); Eq. 8 is then used to describe the applied field intensity for the duration of the simulation. Particles that do not have sufficient momentum to pass the plane of the control electrode are returned to the developer sleeve by the combination of magnetic retention forces and the reverse electrostatic field. Particles that do pass the plane of the control electrode continue on to the paper, propelled by the force from the high vertical electrostatic field [Fig. 3(a)] in the zone between the control electrode ($y = 150\ \mu$m) and the paper ($y = 575\ \mu$m). The converging field intensity shown in Fig. 3(b) continues to "focus" the beam of toner particles as they move toward the paper surface. Final positions of the toner particles on the paper surface after impact, rebound, and settling are shown in Fig. 5.

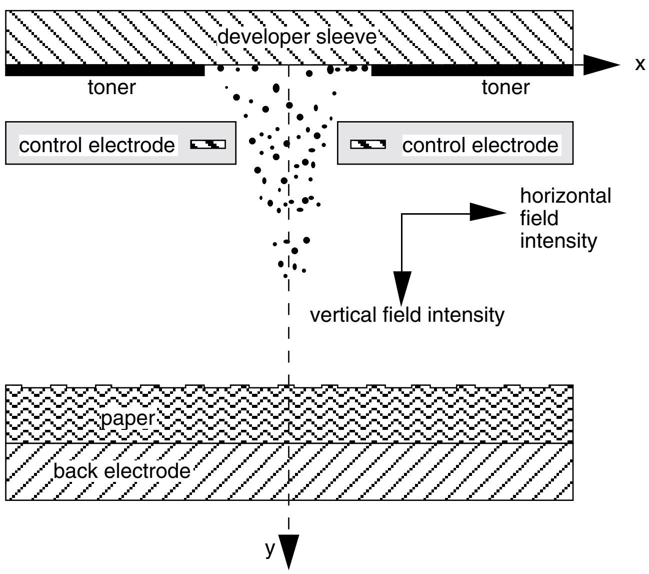

Figure 5. Position of toner particles at the end of the simulation.

Results

Simulation of toner motion provides a visual tool for understanding the influence of each operating parameter of a printer. It has been helpful in guiding research projects by showing what experiments will be most revealing, what parameters to monitor, and what values to expect. A few examples of the observations that can be made in the simulation of a single print pulse are:

- Toner particles follow a converging path to the paper surface.
- Some toner particles strike the control electrode array, but the converging field causes them to pass through the aperture after they rebound.
- Toner is drawn from an area on the developer sleeve that is larger than the printed spot on the paper.

The simulation has also been used to predict the behavior of the TonerJet printing process, for example:

- Estimation of the printing threshold potential
- Estimation of gray-scale printing by varying the time that the control electrode aperture is open
- Demonstrating that initially wrong-sign toner remains on the developer sleeve.

The simulation is also very useful in training classes for introducing the basic operation of a printing technology.

References

1. TonerJet is a registered trademark of Array Printers AB in Sweden.
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5. E. M. Williams, *The Physics and Technology of Xerographic Processes*, John Wiley & Sons, New York, 1984, p. 176.
6. J. C. Maxwell, *A Treatise on Electricity and Magnetism*, Vol. **II**, 3rd ed., Oxford University Press, 1955, pp. 57–58.