Numerical Simulation on Dynamics of Toner and Carrier Particles in Two-Component Magnetic Brush Development System in Electrophotography

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Abstract

We have developed a numerical method for calculating the motion of toner and carrier particles in an electrophotographic two-component magnetic brush development system by using a three-dimensional distinct element method. A characteristic feature of this simulation method is that forces applied to toner and carrier particles include not only magnetic but also electrostatic forces involving a time-dependent electric current in the brush of conductive carrier particles. A parallelization technique for numerical computation was adopted in order to reduce the calculation time. The calculation results qualitatively agreed with the experimental observations in that the number of developed toner particles increases with the development voltage, as well as that some carrier particles adhere to the surface of the photoreceptor drum upon application of high development voltage. It is expected that the presented numerical method can be utilized for the improvement of the two-component magnetic brush development system in electrophotography.

Introduction

The two-component magnetic brush development system, schematically illustrated in Fig. 1 (left), is widely adopted in color and high-speed electrophotography machines [1-3]. Although the system can achieve relatively high quality of printing in comparison with other systems, such as the nonmagnetic single-component system, they occasionally produce certain image defects. Examples of such image defects include bead-carry-out [4,5] and pale halftone defects following a solid image [6]. Many experimental and numerical investigations have been conducted in order to clarify the mechanisms of these defects and to propose effective countermeasures against them [7-10]. However, the physics of the system has not been thoroughly clarified, and therefore its design and improvement rely heavily on trial and error.

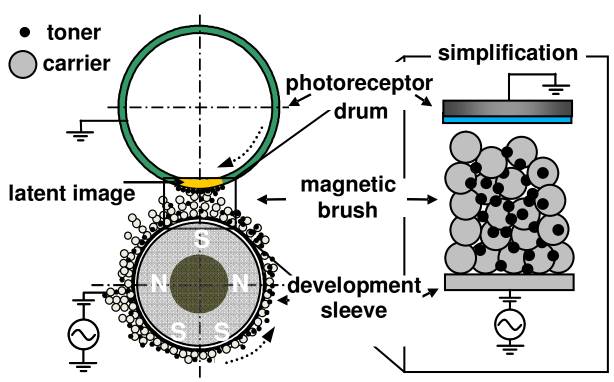


Fig. 1 Two-component magnetic brush development system (left) in electrophotography and simplified geometry at development gap (right).

We are currently developing a numerical simulation tool based on the distinct element method (DEM). Our method takes into account the magnetic force applied to magnetic carrier particles and the electrostatic force applied to both carrier and toner particles. In particular, it is possible to evaluate the effects of the carrier conductivity, which is one of the most important parameters of the system [5]. Although results obtained with the presented numerical method are preliminary, this approach has the potential to be established as a general method for predicting system performance, and it can be utilized for devising measures against image defects.

Modeling

Distinct Element Method

In this study, a three-dimensional numerical simulation model based on the distinct element method was established. The following equations of motion are solved for each particle with six degrees of freedom, including rotations [8]:

$$m_j \ddot{\boldsymbol{u}}_j = \boldsymbol{F}_j, \quad I_j \ddot{\boldsymbol{\varphi}}_j = \boldsymbol{M}_j, \tag{1}$$

where m_j, $\boldsymbol{u}_j$ (= x_j, y_j, z_j), I_j, $\boldsymbol{\varphi}_j$ (= φ_{xj}, φ_{yj}, φ_{zj}), $\boldsymbol{F}_j$, and $\boldsymbol{M}_j$ are the mass, the displacement vector, the moment of inertia, the rotation angle, the applied force vector, and the moment applied to a particle j, respectively. In this study, mechanical interaction force, magnetic force, electrostatic force, air drag, van der Waals force, and gravitational force are included in the applied force and momentum. The fundamental equations and procedures necessary for calculating the forces, except for the electrostatic force, have been reported in the literature [8].

Electrostatic Force

The Coulomb force $\boldsymbol{F}_e$ applied to a charged carrier or toner particle is calculated by integrating $\rho \boldsymbol{E}$ over the volume V of the particle.

$$\boldsymbol{F}_e = \int_V \rho \boldsymbol{E}\, dV \cdot \tag{2}$$

The charge density ρ of the particle and the electrostatic field $\boldsymbol{E}$ are calculated by solving the following coupled partial differential equations.

$$\nabla \cdot (\varepsilon \boldsymbol{E}) = \rho \text{ (Poisson's Equation),} \tag{3}$$

$$-\frac{\partial \rho}{\partial t} = \nabla \cdot (\sigma \boldsymbol{E}) \text{ (Conservation of Charge),} \tag{4}$$

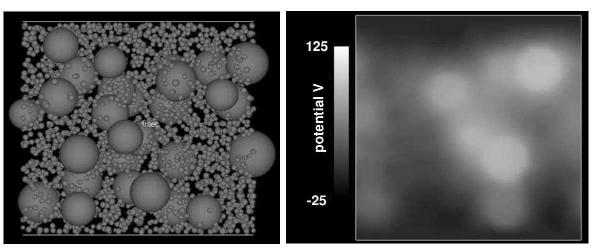
where ε and σ are the permittivity and the conductivity of the particle, respectively. Equation (4) indicates that the model can evaluate the effects of the conductivity of carrier particles as well as the transient charge distribution in the carrier and toner particles [5]. Here, the iterative finite differential method is used for numerical calculation of the charge density ρ and the electrostatic field $\boldsymbol{E}$ [3].

Numerical Method

An excessive amount of time is required for numerical calculation with the above method. The calculation time increases together with the number of particles and the total number of time steps. The calculation time is critically dependent on the process of detecting contact between small toner (6 μm) and large carrier (40 μm) particles, the calculation of the magnetic interaction force between magnetized carrier particles [8], and the calculation of the electrostatic force at each time step. In this regard, the computation time is reduced by detecting contact within virtual cells that include all adjacent particles [11]. We adopted three types of appropriately sized cells for the detection of toner-to-toner contact, toner-to-carrier contact, and carrier-to-carrier contact. Other measures include the simplification of the geometry at the development gap as shown in Fig. 1 (right), the adoption of cyclic boundary conditions [8], and the omission of magnetic and electrostatic force calculations for several time steps. In addition to these improvements on the numerical algorithm, parallel computing was conducted with OpenMP and CUDA.

Verification of Numerical Method

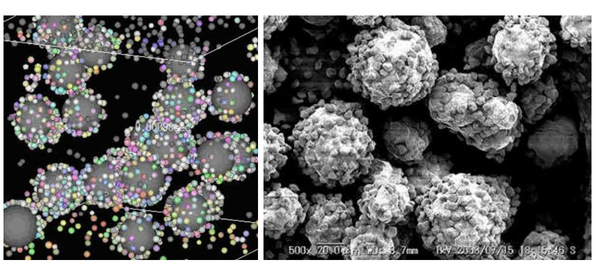
Figure 2 shows the distribution of randomly distributed toner and carrier particles (left) and the calculated distribution of potential (right) in the common area. Since it is assumed that toner particles are negatively charged (15 μC/g) and carrier particles are positively charged (1 μC/g), the distribution of potential corresponds to the spatial distribution of toner and carrier particles, and thus the calculation of electrostatic field appears to be valid.



distribution of particles **distribution of potential**

Fig. 2 Random distribution of toner and carrier particles and calculated distribution of potential.

Figure 3 shows the calculated and the observed distribution of toner and carrier particles after mixing. Negatively charged toner particles adhere to positively charged carrier particles, and the calculation agrees well with the observations. This also supports the adequacy of the proposed numerical method.



calculated **observed**

Fig. 3 Calculated and observed mixture of negatively charged toner and positively charged carrier particles.

Results and Discussion

Figure 4 shows examples of the calculated motion of toner and carrier particles in the development area. The curvature of the development sleeve and the photoreceptor drum is simplified as the change in the development gap between the parallel plates. Although the dynamics of the particles cannot be conveyed with still images, the calculated motion is in qualitative agreement with the observed motion. Since ac voltage (1.5 kV, 6 kHz) is superimposed on the dc development voltage, some toner particles that electrostatically adhere to the carrier particles become free and start vibrating in the development gap synchronously with the ac frequency. As experimentally observed [5,6], some airborne toner particles adhere to the photoreceptor without the brush coming in contact with the photoreceptor (prenip region). When the photoreceptor drum approaches the development sleeve, the carrier brush formed on the sleeve is brought in contact with the photoreceptor and depressed in accordance with the decrease of the gap, and the development of toner particles progresses in this region. Next, the brush becomes free again at the back of the development area (postnip region). As experimentally observed, toner particles vibrate in this region, and some airborne toner particles adhere to the photoreceptor, thus completing the development. The number of

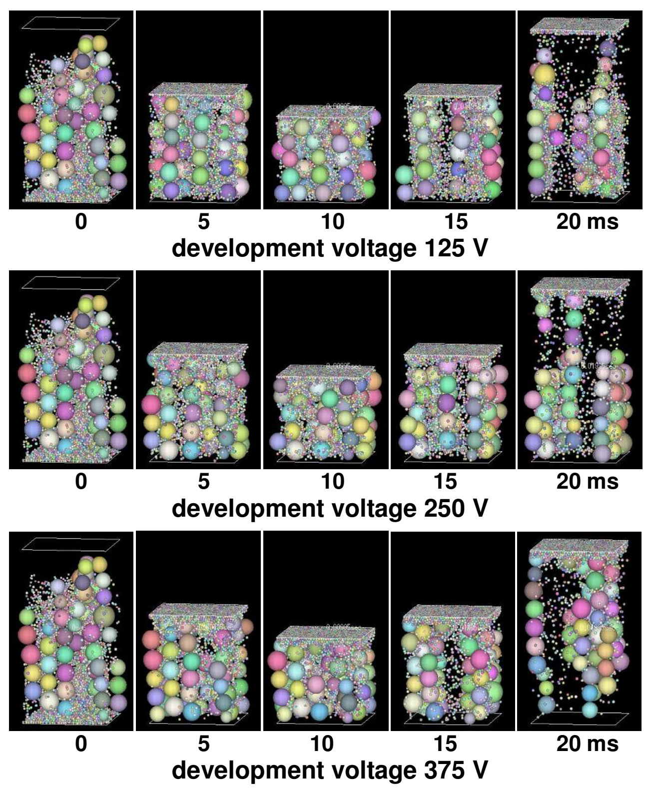


Fig. 4 Calculated motions of toner and carrier particles in development gap (upper: photoreceptor drum, lower: development sleeve).

developed toner particles is large when the applied development voltage is high, which is in agreement with the experimental results [5]. In the postnip region, some carrier particles separate from the tip of the brush and adhere to the photoreceptor, which results in bead-carry-out. The number of carrier particles adhering to the photoreceptor increases when the development voltage is high, which also agrees with the experimental results [5].

Concluding Remarks

A numerical simulation tool has been developed to be utilized in the rational design of the electrophotographic two-component magnetic brush development system and to devise effective measures against image defects appearing in this system. The characteristic features of the proposed tool are as follows.

(1) The model is based on the three-dimensional distinct element method with six degrees of freedom.

(2) Cyclic boundary conditions are adopted.

(3) The distinct element method takes into account mechanical interaction force, magnetic force (including the magnetic interaction force between magnetized carrier particles), electrostatic force, air drag, van der Waals force, and gravitational force.

(4) The effects of transient electric conductions in the brush can be evaluated.

(5) The calculation can be conducted within a reasonable amount of time by adopting certain simplified algorithms and parallel computation.

In this study, the adequacy of the method was verified by comparing calculation results with experimental observations, and it is expected that the tool can be utilized for the improvement of the two-component magnetic brush development system in electrophotography..

Acknowledgement

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