Simulation of Two-Component Development Process for Frontloading Design

Nobuyuki Nakayama, Tomoyuki Ito, Youichi Watanabe, Nobuyuki Hirooka and Tomohiro Seko; Fuji Xerox Co., Ltd.; Ashigarakami, Kanagawa/Japan

Abstract

This report describes simulation technologies for digital frontloading of two-component development process in electrophotography. Electrophotography entails using multi-physics involving phenomena with yet unclear mechanisms such as air breakdown, tribocharging and powder dynamics. Thus, it requires much effort and many resources to develop electrophotography products. Numerical simulation is widely recognized as one of valid approaches to overcome these difficulties in product design. A tool for simulating the two-component development process has been developed including particle motion calculation using the Distinct Element Method and electric filed calculation using the Finite Element Method. The tool working on PC clusters is equipped with force decomposition method as a high-efficiency parallel computation algorithm to reduce calculation time. In addition, GUIs, and an online portal for PC clusters has been developed to support product designers utilizing the simulation tool. Validity of the tool was confirmed by comparison of developed toner mass and developer mass on development roller with the experimental results.

Introduction

In product development of multi-functional copiers and printers, optimizations of electrophotography process parameters are required in advance of hardware design. The quality of the optimization determine the performance of the product and it also affects product development period and costs. Therefore, simulation technologies are used to reduce these efforts by digital frontloading, that is, to design parameters and verify performances virtually in prior to manufacturing [1]. Electrophotography entails using multi-physics involving phenomena with yet unclear mechanisms such as air breakdown, tribocharging and powder dynamics. Because no commercial tools to simulate these phenomena are available, developing of simulation tools and a system to support product designers utilizing the tools is important.

In this study, a simulation tool of the two-component development process for digital frontloading has been developed including particle motion calculation using the Distinct Element Method (DEM) and electric filed calculation using the Finite Element Method (FEM). To overcome the difficulties in computation cost in the particle calculation, high-efficiency parallel computation algorithms were investigated and the force decomposition method [2] was employed. In addition, GUIs, and an online portal for PC clusters have been developed to support product designers utilizing the simulation tool. Validity of the tool was investigated by comparison of developed toner mass and transported developer mass on development roller with the experimental results.

Simulation Method

Two-Component Development Process

Two-component development process consists of several separated functions; developer transport in auger screw system, transport on a development roller with a magnet inside, toner image formation in an electric field formed between development roller and photoreceptor. To simulate roller transport and image formation process and to evaluate the qualities of these process numerically, particle motion calculation using DEM are used.

A schematic drawing of roller transport and image formation in development process is shown in Figure 1. Magnetized carrier beads with several ten microns in diameter form chain clusters (magnetic brushes) on a rotatory sleeve in the magnetic field created by a stationary permanent magnet. Toner particles with several microns in diameter electrostatically attached to magnetic bead brushes are transported to the development nip with rotation of the sleeve. A magnetic blade trim developers and form thin layer in advance of image formation in the development nip. In the development nip, electrostatic force acts on toners and they move to electrostatic latent images on photoreceptor surface to form real images.

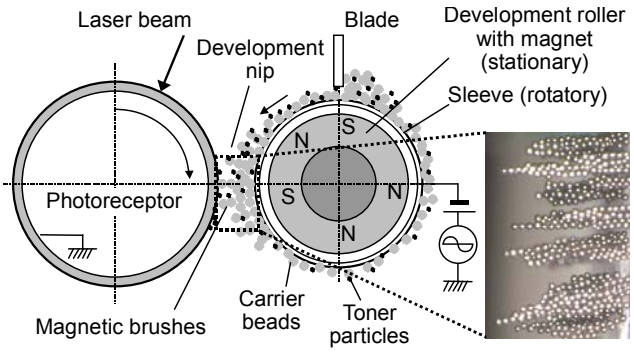


Figure 1*. Two-component development process*

Numerical Algorithm of Motion Calculation

As mentioned above, it is required in the development parameter optimization to evaluate the qualities of development process. The qualities include, for example, developer mass on the sleeve, developed toner mass both in image and background, image degradation such as bead-carry-out, tail edge deletion and starvation, etc. One of possible methods to simulate these phenomena is DEM. In the DEM calculation, the following

momentum equation is solved for each carrier bead or toner particle.

$$m_j \ddot{\mathbf{u}}_j = \mathbf{F}_j, \quad \mathbf{F}_j = \mathbf{F}_{cj} + \mathbf{F}_{mj} + \mathbf{F}_{ej} + \mathbf{F}_{dj} + \mathbf{F}_{aj} + m_j \mathbf{g},$$
(j=1,…, N; N: number of particles), (1)

where m_j, $\mathbf{u}_j$, and $\mathbf{F}_j$ are mass, displacement vector, and applied force vector to the j-th bead, respectively. Mechanical contact force $\mathbf{F}_{cj}$, magnetic force $\mathbf{F}_{mj}$, electrostatic force $\mathbf{F}_{ej}$, air drag $\mathbf{F}_{dj}$, attractive force $\mathbf{F}_{aj}$ and gravitational force $m_j\mathbf{g}$ are included in the applied force. Here, $\mathbf{g}$ designates the gravitational constant.

The mechanical contact force was determined assuming the Voigt model. The elastic force in the normal direction at the contact point was estimated assuming the Hertzian theory and the force in the tangential direction was assumed to be proportional to the normal force. Viscous components of forces proportional to displacement velocity and viscous coefficient are added to these forces.

The magnetic force $\mathbf{F}_{mj}$ acting on the j-th carrier bead with the magnetic dipole moment $\mathbf{p}_j$ is given by the following expressions under the assumption that each bead behaves as a magnetic dipole placed at the center of the bead [5].

$$\mathbf{F}_{mj} = (\mathbf{p}_j \cdot \nabla)\mathbf{B}_j . \quad (2)$$

The magnetic flux density $\mathbf{B}_j$ at the position of the j-th bead and magnetic moment $\mathbf{p}_j$ are

$$\mathbf{B}_j = \mathbf{B}_j' + \sum_{\substack{k=1 \\ j \neq k}}^{N} \frac{\mu_0}{4\pi} \left(\frac{3(\mathbf{p}_k \cdot \mathbf{r}_{kj})}{|\mathbf{r}_{kj}|^5} \mathbf{r}_{kj} - \frac{\mathbf{p}_k}{|\mathbf{r}_{kj}|^3} \right), \quad (3)$$

$$\mathbf{p}_j = \frac{4\pi}{\mu_0} \frac{\mu - 1}{\mu + 2} \frac{a_j^3}{8} \mathbf{B}_j , \quad (4)$$

where μ_0 is the permeability of free space, μ and a_j are the relative permeability and the diameter of the bead, respectively, and $\mathbf{r}_{kj}$ is the position vector from the k-th to the j-th bead.

The electrostatic force is estimated by the product of the electric field $\mathbf{E}$ and the charge of the developer. The electric field and the induced charge were determined by solving the following two coupled equations, the Gauss's law and the conservation of charge.

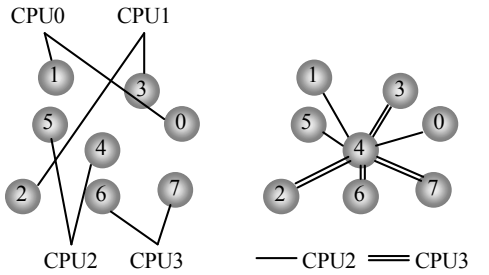
$$\nabla \cdot (\varepsilon_0 \varepsilon_r \nabla \phi) = -\rho , \quad \nabla \cdot (\sigma \nabla \phi) = \frac{\partial \rho}{\partial t} , \quad (5)$$

where ϕ is potential, ε_0, ε_r, σ and ρ are permittivity in free space, relative dielectric constant, conductivity, and space charge, respectively. An iterative FEM was used to calculate the coupled differential equations. In addition, to consider electrical effects of developers and to estimate induced charge in the conductive carrier beads, the electric properties were distributed to the corresponding elements. That is, the calculation area was divided into many small elements in order to sham spherical carriers and toners by quadrilateral or hexahedron elements. Then, the dielectric constant, conductivity and space charge of the elements which belong to the carriers or toners are set to appropriate values.

Parallel Computation Algorithm

It is supposed to take more than a few weeks to compute electromagnetic interactions and motions of more than several ten thousand of carrier beads and toners. On the other hand, it should be reduced to less than several ten hours in practical use of parameter optimization in product development. Parallel computation using PC clusters is a useful technique to shorten computing time.

Parallel methods of particle motion calculation are described in Figure 2. In the case of particle decomposition method as described in Figure 2 (a), calculations of interactions and motions of N/P (N: number of particles, P: number of processors) particles are assigned to each processor. In the figure, the interactions and motions of 8 particles are computed by 4 processors, that is, calculations of each 2 particles are assigned to each processor.



(a) Particle decompositon (b) Force decomposition

***Figure 2**. Parallel computation method*

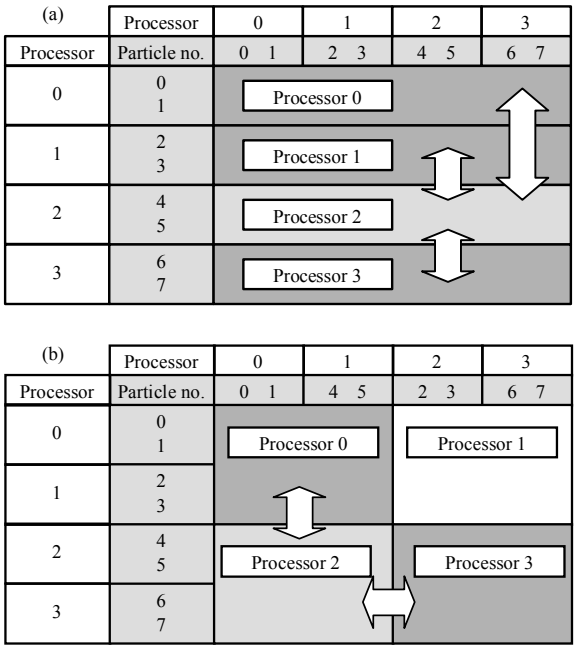


***Figure 3**. (a) Concept of particle decomposition method and (b) force matrix which defines a rule of interaction computation in force decomposition method*

The concept of particle decomposition method is shown in Figure 3 (a). Each processor calculates interactions of the assigned 2 particles with the other particles, then sum them up to obtain updated forces. Then, updated coordinates of particles are obtained by solving the equations of motion using updated forces. Subsequently, a processor communicates updated coordinates to all other processors for the computation of the next time step. The communication cost is large and it is supposed to limit the parallel efficiency. Calculation and communication time spent for the motion calculation of 28800 beads with magnetic interactions are shown in Figure 4 (a). 16 CPUs (Pentium(R) 4 2.8GHz) connected by GbE network were used for the calculation. In the figure, it is shown that computation time decreases proportionally with the increase in number of processors, on the other hand communication time is almost constant. This tendency tells us that the parallel efficiency will be saturated in the larger number of processors.

Force decomposition method [2] was introduced to improve parallel efficiency, as is described in Figure 2 (b) and Figure 3 (b). In the method, motion calculations of N/P particles are assigned to each processor same as in the particle decomposition method. Meanwhile, calculations of the interaction forces are performed according to a force matrix shown in Figure 3 (b). The force matrix divides interactions between particles into groups, and assigns each group to different processors. For example, consider computations of interactions for particle no. 4 which is assigned to processor 2. Processor 2 is used for calculation of interactions with particles no. 0, 1, and 5 and processor No. 3 is for interactions with particles no. 2, 3, 6 and 7. The processor calculates partial sum of forces on the assigned interactions, then communicates among the processors to obtain total sum of forces. After calculation of forces and coordinates, the updated coordinate of the particle no. 4 is communicated to the processor 0 and 3 except the processor 1. The information of coordinate on the processor 1 is not required, because assigned group of interactions does not include the particle no. 4. Thus, the force decomposition method does not have to communicate between all processors, and it can decrease the amount of communications. Figure 4 (b) shows that the computation time decreases with the number of processors same as in the particle decomposition method, and that the communication time also decreases proportionally with the number of processors. As a result, parallel computation efficiency of 16 processors is 76 % with the force decomposition method, while the efficiency is 44 % with the particle decomposition method.

Simulation Supporting System

GUI was developed to support product designers utilizing the simulation tool. An example of GUI for simulation of roller transport of developer is shown in Figure 5 [4]. The procedure of the simulation is as follows:

1. create 2D coordinates of development housing.
2. calculate magnetic field around the magnetic roller from assumed magnetic flux distribution on the sleeve surface.
3. execute developer transport simulation using results obtained in procedure 1 and 2.

Creation of the data, execution of calculation and visualization can be done using the GUI.

An online portal was also developed for product designers to utilize many simulators and PC clusters with no difficulty and special knowledge. The portal integrates cluster computer resources with heterogeneous operating systems and architectures, and then it provides virtually assembled one computer with secure environment [6].

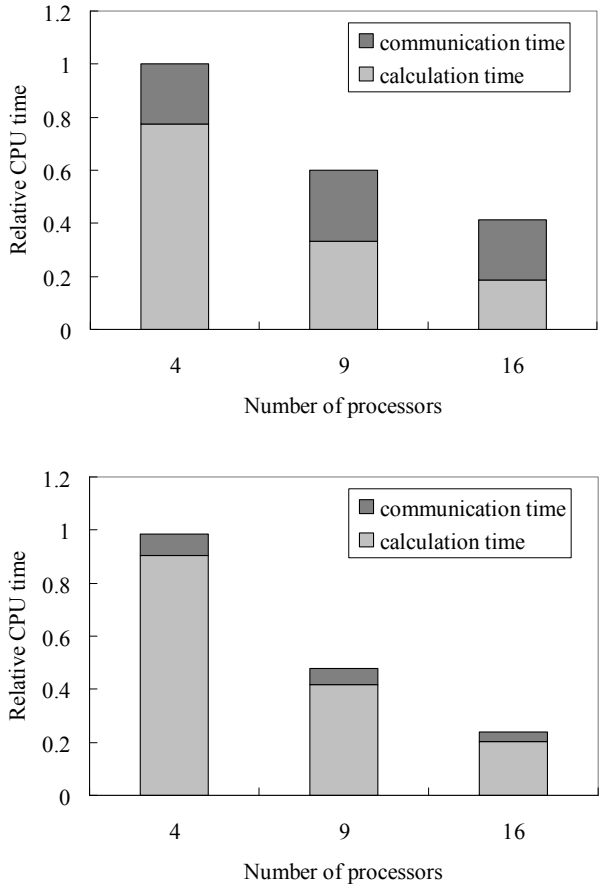


***Figure 4**. CPU time of magnetic interaction calculation (a) by the particle decomposition method and (b) by the force decomposition method*

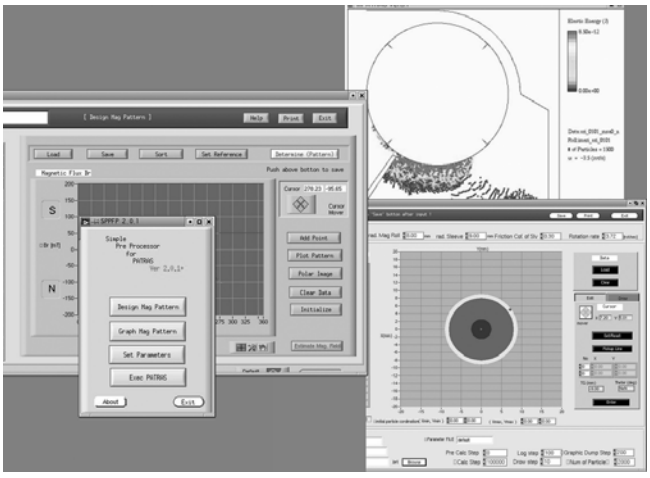


***Figure 5**. GUI for developer transport simulation*

Simulation Results

Simulated result of image forming process near development nip is shown in Figure 6. Solid latent image was formed on the photoreceptor numerically and the motions of approximately 38000 carrier beads and toners were calculated. Solid toner image on the photoreceptor surface in the post-nip is shown in the figure.

Developed toner mass on photoreceptor in solid image forming processes were calculated using 2D model for various toner charge (-17.0 ~ -27.0 μC/g), and voltage between development roller and photoreceptor (100 ~ 500 V). Compared results of developed toner mass in the calculation and experiment are plotted in Figure 7. The results show good correlation of calculated and experimental values and it tells us that the tool is valid for optimization of development parameters. Otherwise, the calculated values are approximately 1.4 times larger than the experimental values, because electromagnetic interactions are not evaluated precisely by the 2D model.

Developer mass on sleeve after trimming process by a magnetic blade was also calculated using both 2D and 3D models. The results for different gaps between blade and sleeve (0.3 ~ 0.7 mm) and surface roughness of sleeve (2 ~ 4 μm in mean center line roughness) are plotted in Figure 8 comparing with the experimental values. Both 2D and 3D results show good correlation of calculated and experimental values and it is also shown that the 3D model give quantitatively precise results.

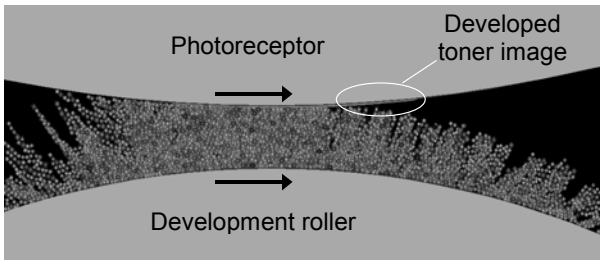


***Figure 6**. Simulated toner and carrier behavior near development nip*

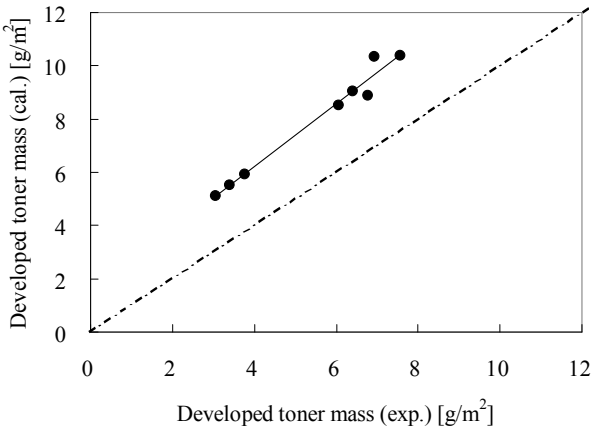


***Figure 7**. Comparison of calculated developed toner mass per area with experimental results*

Conclusions

In this study, a simulation tool of the two-component development process for digital frontloading has been developed including particle motion calculation using the Distinct Element Method (DEM) and electric filed calculation using the Finite Element Method (FEM). The tool equipped with the force decomposition parallel method showed remarkable high efficiency compared with the particle decomposition method. In addition, GUIs and an online portal for PC clusters are supposed to valid for product designers utilizing the simulation tools. Validity of the tool was confirmed by comparison of calculated developed toner mass and developer mass on sleeve with the experimental results for various development parameters.

References

[1] N. Nakayama and T. Ito, "Xerography Process Simulation -Tools for frontloading design-," Fuji Xerox Technical Report, 18, 15 (2008).

[2] S., Plimpton and B., Hendrickson, "A New Parallel Method for Molecular Dynamics Simulation of Macromolecule Systems," J. Comp. Chem., 17, 326 (1996).

[3] N. Nakayama, T. Ito, T. Nagao, H. Mukai, N. Hirooka and T. Seko, "Simulation of development and transfer process," Fuji Xerox Technical Report, 16, 36 (2008).

[4] T. Seko, "Design of Electrophotographic Development Process by Numerical Simulation," Jour. Imaging. Soc. Japan, 43, 164 (2004).

[5] N. Nakayama, Yoichi. Watanabe, Yasuaki Watanabe and H. Kawamoto, "Experimental and Numerical Study on the Bead-Carry-Out in Two Component Development Process in Electrophotography," Jour. Imaging. Sci. and Technol., 49, 537 (2005).

[6] S. Ito, "Utility business model GridASP," LS DYNA Users Week 2007, (2007).

Author Biography

Nakayama, Nobuyuki holds a BS degree in Physics from Tohoku Univ. (1983) and a Dr. degree in Mechanical Engineering from Waseda Univ. (2003). In 1983, he joined Fuji Xerox Co., Ltd., where he has been engaged in a research on electrophotography and is currently studying on electrophotography process simulation. He is a member of the Imaging Society of Japan and the Japan Society of Mechanical Engineers.

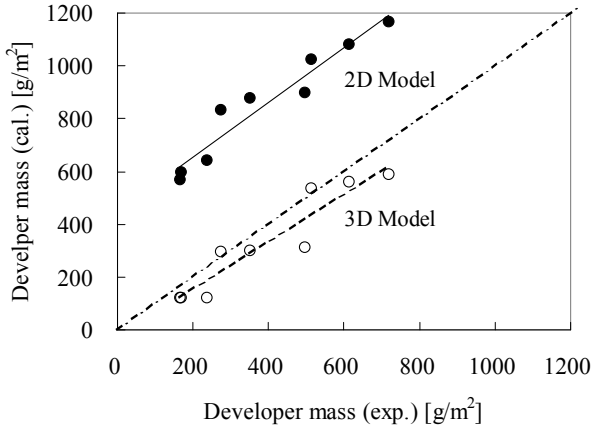


***Figure 8**. Comparison of calculated developer mass per area with experimental results*