Numerical Simulation of Carrier Behavior Around a Magnet Roll in a Two-Component Developer Unit in Electrophotography

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Abstract

A new particle simulator to analyze the behavior of carrier beads around a magnet roll in a two-component developer unit in electrophotography has been developed. The simulator, which is based on the Discrete Element Method, including the magnetic interaction force among particles in a magnetic field, adopts parallel processing with MPI and/or OpenMP. Parallel processing of the particle simulator with several processors provides excellent performance to simulate the behavior of a realistic amount of particles in a practical time. The simulation results obtained for tens of thousands of carrier beads reveals not only realistic particle behavior around a magnet roll but also the quantitative relation between the stress on the carrier and the amount of carrier beads that passes through a gap between the doctor blade and the magnet roll. These are very important parameters to obtain high-quality images in a two-component developer unit.

Introduction

In a two-component development process, control of the behavior of carrier beads around a magnet roll in a developer unit in electrophotography is one of the most important factors in obtaining high-quality images and maintaining high reliability. The design of an improved electrophotography system requires an understanding of the behavior of the carrier beads inside the developer unit. However, since this phenomenon is not visible, correctly identifying their behavior is very difficult.

Computer simulation is a promising tool for analyzing the behavior of carrier beads, for which a number of simulators have been developed for calculating the behavior of carrier beads. The reported simulation results will open the possibility of computer simulation.[1,2]

The present study reports the development of a parallel processing particle simulator, which is based on the Discrete Element Method, including the magnetic interactive force, specialized for analyzing the behavior of carrier beads.[3,4] Message Passing Interface and OpenMP are adopted as a parallel processing method for the simulator. Parallel processing is expected to increase the calculation performance of the particle simulation. Using this high-performance particle simulator, the stress on the carrier beads and the transfer activity of the carrier beads on the magnet roll are estimated.

Calculation Method

Discrete Element Method (DEM), including the magnetic interaction force among particles in a magnetic field, is a well-known method for numerical simulation of the behavior of carrier beads in a two-component developer unit. The particle simulator described herein was basically developed according to this conventional method.

The Domain Decomposition Method (DDM) and Message Passing Interface (MPI) were adopted for parallel processing on a computer cluster system. In the DDM, the target space of simulation is partitioned into several domains, and the behavior of particles in each domain is calculated by one computer, which belongs to a computer cluster system, as shown in Figure 1.

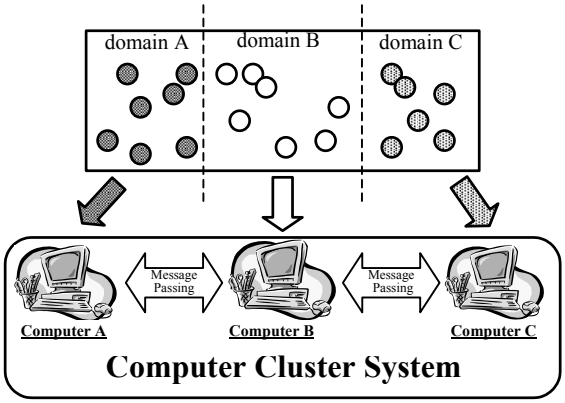

Figure 1. Parallel processing with domain decomposition on a computer cluster

Physical state data of a number of particles in a domain near the boundary are required for calculating the particle behavior in neighboring domains and exchanging data among the domains with MPI. The particles for which data are required are determined according to position and cut-off distance, as shown in Figure 2. The cut-off distance is the effective distance of magnetic interaction between two particles.

In addition, another method, OpenMP, is adopted for parallel processing. OpenMP is a specification for shared memory parallel programming. The simulation source code was modified by inserting a number of OpenMP directives in the correct position of the source code. Implementation and execution of a simulation is easy compared with MPI parallel processing.

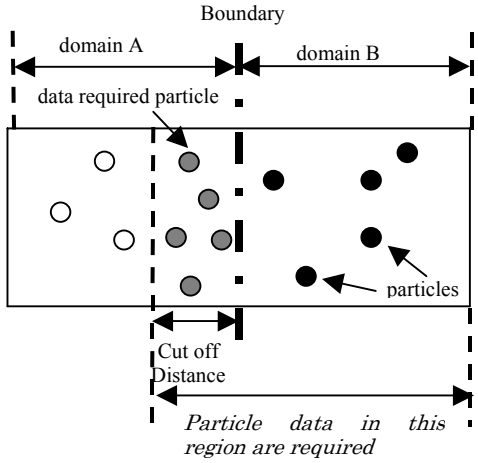

Figure 2. Required particle data for calculation in a sub domain with "Cut-off Distance"

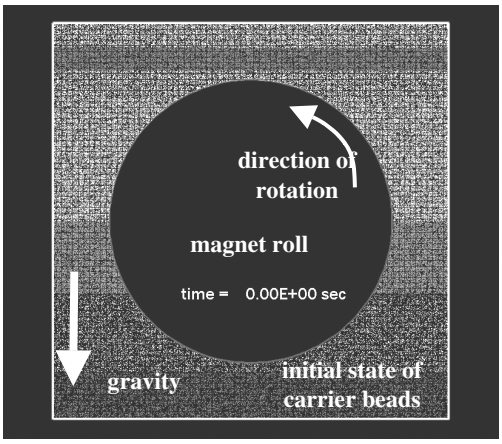

Figure 3. Simulation model layout (initial state)

Results

Performance Test of Simulator

Simulations for performance testing of the simulator with parallel processing were performed under several parallel processing conditions with a simple layout, as shown in Figure 3.

In the initial state, 10,000 ferromagnetic particles are dispersed randomly around a magnet roll. Particles are grayscaled to facilitate recognition of the initial positions of particles. The magnet roll rotates in the counter clockwise direction, and the direction of gravity is downward.

A domain decomposition procedure in the simulator for parallel processing with MPI is available for dynamically partitioning an entire region into domains in order to balance the number of particles in each domain.

Hybrid parallel processing with OpenMP and MPI is also available. A computer cluster system constructed of shared memory type multi-CPU computers is used for the hybrid parallel processing.

Table 1: Performance Test Results with Parallel Processing

CPU#	1	2	4	2	4	8
Method	-	OpenMP	OpenMP +MPI	MPI	MPI	MPI
Relative speed	1	1.43	2.09	1.45	2.39	2.91
Parallel efficiency	-	0.72	0.52	0.73	0.6	0.36

The results are shown in Table 1. All of the computers used in the performance test have the same specifications.

The results show that the simulation speed increases according to the number of processors. Using eight processors, the simulation speed is approximately 2.9 times faster than calculation using one processor. The parallel efficiency is 0.36 for the same simulation. Although the parallel efficiency is not so good, the simulation time is reduced by 65%, which is important in practical application.

These results indicate that MPI parallelization is more efficient than OpenMP parallelization. The reasons for this are unclear.

Conformation of 45,499 ferromagnetic particles on a plate with a magnet under the plate was calculated, and the result is shown in Figure 4.

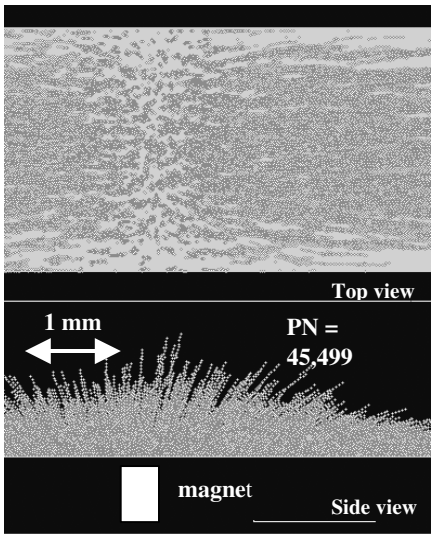

Figure 4. Shape of magnetic brush on a plate (Simulation result)

According to the magnetic field of the magnet, innumerable chain-shaped clusters of particles are found on the plate. This formation of particles is similar to the observation result for carrier beads in a magnetic field. The simulator appears to show well the behavior of carrier beads on a magnet roll.

Analysis of the Behavior of Carrier Beads

The amount of carrier beads transported through the gap between a doctor blade and a magnet roll (doctor gap) and the stress on the carrier beads are calculated using the simulator. The simulation

conditions are the same except for the number of particles. The number of particles is selected from 40,000, 80,000 and 160,000, and other simulation parameters are the same in all of the simulations. The simulation conditions using 40,000, 80,000, and 160,000 particles are called conditions A, B, and C, respectively.

The initial state of the simulation model is shown in Figure 5. The magnet roll rotates in the counterclockwise direction, and the carrier beads, which are dispersed in the space at the right-hand side of the magnet roll in the initial state, are transported in the direction of the magnet roll rotation. The amount of carrier beads is counted in region A, indicated by a rectangle in Figure 5, and the stress on the carriers is sampled in region B, As indicated by another rectangle at the right-hand side of the doctor blade, as shown Figure 5.

These simulation results are shown as a snapshot in Figure 6. Snapshot A is the result of simulation under condition A. Snapshot B and Snapshot C are the results of simulations under conditions B and C, respectively.

Figure 6 shows the difference in the space of the upper right-hand side. In snapshot C, several carrier beads are present, filling the space. In contrast, the amount of carrier beads in snapshot A is small, and the space is almost empty. In snapshot B, only half of the space is filled. However, the space at right-hand side of the doctor blade is fully filled with carrier beads in every snapshot. In addition, the shape of carrier beads after passing through the doctor gap appears to be the same.

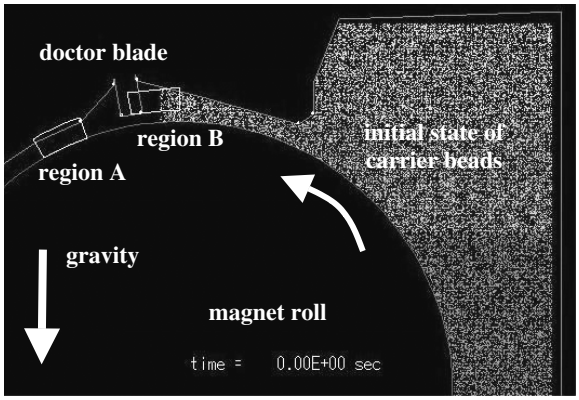

Figure 5. Simulation model layout (initial state)

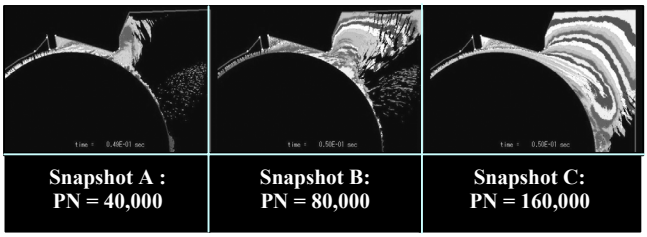

Figure 6. Snapshots of carrier bead flow. Number of particles is 40,000, 80,000 and 160,000, respectively.

For each of the simulation conditions shown in Figure 6, the average number of carrier beads inside region A, indicating the amount of carrier beads transported through the doctor gap, is shown in the left-hand bar chart of Figure 7, and the stress on the carrier beads inside region B is shown in the right-hand bar chart of Figure 7.

Both bar charts in Figure 7 show that the differences between condition A and condition B are small, but the simulation results under condition C are somewhat different. A difference in the stress of the carrier beads is clear. The stress value of condition C is twice as large as those of conditions A and B, indicating that the number of particles is significant with respect to the estimation of the stress on particles using the simulator. On the other hand, the amount of carrier beads passing through the doctor gap under condition C is 20% larger than the others. A 20% increase in the amount of carrier beads is also significant factor in developer functions.

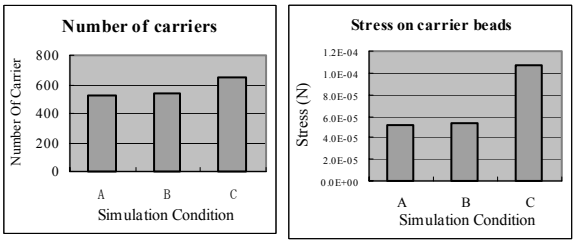

Figure 7. Number of carriers and stress on carrier beads in simulation conditions A, B and C

The results shown in Figure 7 also indicate that the increase in stress on the carrier beads in front of the doctor blade is not very effective for increasing the amount of carrier beads through the doctor gap. The design of a new developer unit with low stress on the developers should be considered.

Based on the results shown in Figure 6 and Figure 7, filling up the upper right-hand space shown in Figure 6 with carrier beads (Snapshot C) appears to increase the amount of the carrier bead flow and the stress on carrier beads near the doctor blade. Simulation result using a large amount of particles reveals the carrier bead behavior, as in snapshot C. On the other hand, simulations using a small amount of particles, as in condition A, may not show the particle bead behavior. These are completely different phenomena and some kind of phase transition should be occurred in the carrier bead flow. Therefore, in carrier bead simulations it is essential to use an adequate number of particles.

Conclusion

A new particle simulator for analyzing the behavior of carrier beads around a magnet roll in a two-component developer unit was developed. Although the newly developed simulator is based on the Discrete Element Method, including the magnetic interaction forces among particles, the simulator realizes high performance and high availability with parallel processing using MPI and/or OpenMP. Using this simulator with eight processors, the simulation time is reduced by 65%.

Simulation results obtained using the developed simulator shows that the amount of particles used in simulation influences the behavior of the carrier beads, which suggests that to obtain an accurate simulation requires an adequate amount of particles.

In addition, the results reveal the quantitative relation between the stress on the carrier beads and the amount of carrier beads transported through a gap between the doctor blade and the magnet roll. The design of a new developer unit with optimized the stress and the amount of carrier beads should be considered and this new developed particle simulator may be useful to design such a new developer unit.

References

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Author Biography

Takahiro Watanabe received his BS in physics from Hokkaido University (1986) and also received MS in physics from Tohoku University (1988). He joined Ricoh in 1988 and he has been developing high performance particle simulator for electrophotography since 1998.