New Technology for Improving Image Density Uniformity in the Electrophotographic Process

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Abstract

This paper introduces a new method to reduce periodic density unevenness caused by eccentric rotation of the photoconductor drum and development roller in an electrophotographic printer. In a previous study, a method for controlling periodic density unevenness by using developing bias was proposed. The developing bias is controlled periodically to correct density unevenness. However, no control effects are obtained in low density images; rather, the control somewhat increases the density unevenness.

In this study, we developed a new method that reduces the periodic density unevenness through modulation of both charging bias and developing bias based on the rotational periods of the photoconductor drum and development roller. Each bias is periodically changed such that the changes in the developing field due to the eccentric rotation of the photoconductor drum and development roller are cancelled, thus suppressing the periodic density unevenness. Experiments we conducted confirmed that the new method improves periodic density uniformity better than the previous method. The new method guarantees density uniformity is obtained without the use of high-precision components.

Introduction

Variable data printing capabilities have helped to expand electrophotographic printing into the production printing and high-end office printing markets. The Ricoh Company has already launched three types of color POD (print on demand) printers; the Pro C900 in 2008[1], the Pro C901S in 2010[2], and the Pro C751EX/651EX in 2011[3]. These products are reputed for having high speed printing capability, for being adaptable to various types of paper, and for their advanced customer service programs. Naturally high-quality printing is demanded in the production printing market, and it is assumed that electrophotographic printing can compete with offset printing in terms of commercial printing quality factors such as image density uniformity and stability. As a result, electrophotographic printers are becoming increasingly available in this market. To solidify and strengthen electrophotographic printing's position in the production printing market, it is essential to improve its image density uniformity.

One problem with electrophotographic printing image quality is uneven image density, which is mainly caused by two things. The first is the fluctuation of electrostatic factors, such as the charge on the photoconductor drum, exposure energy, the photosensitivity of the photoconductor drum, the electric resistance of the development roller, and the charge distribution of toner particles. The second is the fluctuation of mechanical factors such as the mechanical accuracy, i.e., the rotation accuracy of the photoconductor drum and development roller, which is one source of developing gap fluctuation. The periodic density unevenness caused by the fluctuation of mechanical factors occurs at short intervals and is easily noticeable. One possible way to address the problems of rotation fluctuation of the photoconductor drum and the development roller and developing gap fluctuation is to use high-precision components. However, such components lead to an increase in cost, which should be avoided as much as possible.

Another approach to solving the problems is a control method to suppress the rotation fluctuation. Chen et al. [4] proposed a process control method for controlling photoconductor drum velocity, and Cho et al. [5] proposed a control method using disturbance attention by modulating a brushless DC motor pulse for the photoconductor drum. These methods can suppress the periodic density unevenness due to velocity fluctuation. However, the developing gap fluctuation due to eccentric rotation of the photoconductor drum and development roller still remains. To reduce the periodic density unevenness caused by eccentric rotation, Sasaki [6] proposed a control method using modulation control of developing bias. This method can periodically control the developing bias to correct the density unevenness in high density images such as solid images. However, no control effects are obtained in low density images; rather, the control somewhat increases the density unevenness. In a low density image, the image density also depends on the background potential. Modulating the developing bias causes a change in background potential and may increase density unevenness. Thus, a control method for electrophotographic printers is required to correct the periodic density unevenness in low density images.

In this paper, we introduce a new method that improves the periodic density unevenness by controlling the developing and charging biases to correct the developing field. The method guarantees density uniformity and enables high quality printing images to be obtained at low cost.

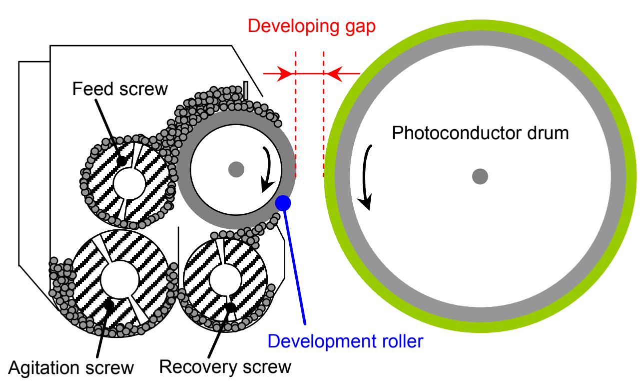
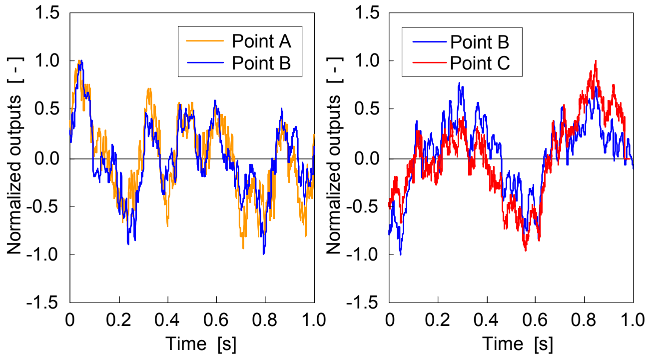


Figure 1*. Developing gap between photoconductor drum and development roller*



(**a**) *At points A and B* (**b**) *At points B and C*

***Figure 2**. Comparison of density unevenness at points A, B, and C*

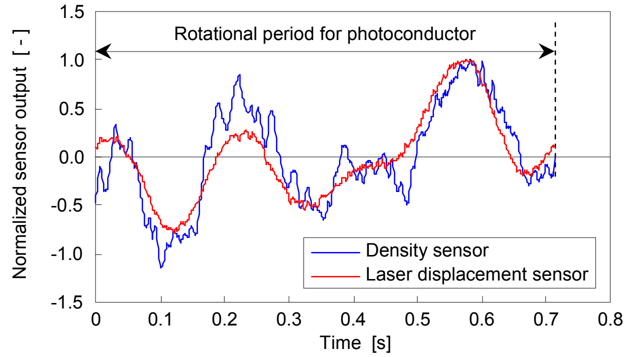


***Figure 3**. Comparison of uneven rotation and density unevenness*

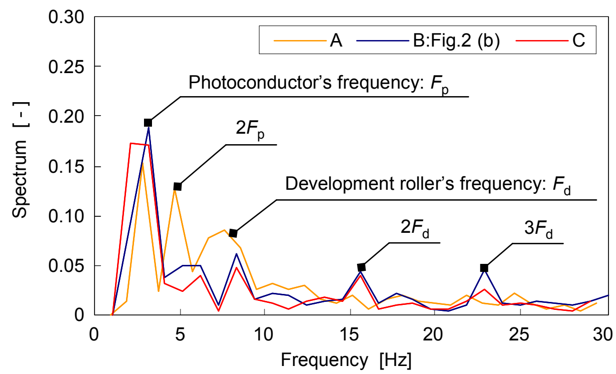


***Figure 4**. FFT analysis results for density unevenness*

Periodic Density Unevenness

Outline of Periodic Density Unevenness

In the printing process, developing bias is applied between the photoconductor drum and development roller and the toner is developed on the photoconductor drum surface in accordance with the latent image. It is known that the development field intensity is generally proportional to the electrical potential between the photoconductor drum and development roller, and is inversely proportional to the developing gap between them (Figure 1) [7]. Therefore, if the developing gap changes due to the eccentric rotation of the photoconductor drum and development roller, the development field will change correspondingly and the result will be periodic density unevenness. We consider the eccentric rotation to be the main factor causing the periodic density unevenness.

Analysis of Periodic Density Unevenness

To determine whether the periodic density unevenness is caused by another factor besides the developing gap, we investigated three printing processes and measured the density unevenness profiles for each of them. The measure points A, B, and C are as below.

A: After the development process

B: After the 1st transfer process

C: After the fusing process (on the paper)

At the points A and B, toner patterns were measured with diffuse reflex sensors. At point C, the lightness on the paper was measured with a scanner. The sampling period of the image density sensor was 1 ms and the scanner resolution was 600 dpi. The toner pattern was made as a solid pattern; the vertical scanning length was approximately 900 mm. The pattern length was made equivalent to about three times the circumferential length of the photoconductor drum to eliminate the disturbance error.

Figure 2 (a) shows a comparison of density unevenness profiles at points A and B. Figure 2 (b) shows the same at points B and C. The sensor and scanner outputs were normalized to compare each profile. From the figures, it can be seen the density unevenness profiles (A and B, B and C) are very similar. This shows that the density unevenness is affected very little by the post-development processes.

Next, to clarify the relationship between the eccentric rotation and the density unevenness, we measured the eccentric rotation of the photoconductor drum with a laser displacement sensor. Additionally, an image density sensor was affixed to the intermediate transfer belt to measure the image density on the belt. Both sensor outputs were recorded synchronously.

Figure 3 shows a comparison of the eccentric rotation of the photoconductor drum and the periodic density unevenness in the drum's rotational period. The figure makes it clear that the wave profiles for them closely coincide. From this we determined that the eccentric rotation of the photoconductor drum is one of the major causes of the periodic density unevenness.

Figure 4 shows the FFT analysis results for the density unevenness in Figure 2. It can be seen that most of the density unevenness peaks arise at the rotational period of the photoconductor drum and the development roller. It also confirms that 2nd and 3rd order oscillation can be observed in this machine. These results led us to determine that periodic factors other than the eccentric rotation of the photoconductor drum and development roller were negligible.

From these analysis results, it was confirmed that:

1. The eccentric rotation of the photoconductor drum and development roller was the major cause of the periodic density unevenness.
2. The periodic density unevenness arises from the fluctuation of the developing gap caused by eccentric rotation.

Newly Developed Improvement Method

Outline of New Method

Our newly developed method improves the periodic density unevenness by modulating the developing and charging biases on the basis of the rotational period of the photoconductor drum and development roller. Modulating the charging bias keeps the development field stable in low density images, enables the new method to suppress the periodic density unevenness in low density images better than the previous method.

Experimental Setup

Figure 5 shows the experimental setup. It consists of a general image forming apparatus using a two-component development process. It includes a photoconductor drum, a development roller, a charge roller, a high voltage power supply, an intermediate transfer belt, and an image density sensor. Two photo interrupters and a personal computer (PC) were added to it as well. The photo interrupters were located close to the rotation axes of the photoconductor drum and development roller respectively, and the image density sensor was located on the intermediate transfer belt. The PC recorded the outputs from the image density sensor and photo interrupters synchronously. The sampling time and control period for the high voltage power supply were both 1 ms. The high voltage power supply, which applies a voltage to the development roller and charge roller, is controlled by the PC. Since the PC is equipped with a digital signal processor (DSP) board, the developing and charging biases are modulated on the basis of each control table in real time. All measurements and controls were carried out on the basis of the photo interrupter outputs.

Design of Control Tables

Figure 6 shows the flowchart for determining the control tables for the developing and charging biases. First, as indicated, the solid image pattern is formed and detected. The pattern length is made equivalent to about three times the circumferential length of the photoconductor drum to obtain the data for periodic uneven density. Next, the control tables for the developing bias $V_b(t)$ are calculated and determined on the basis of periodic density unevenness and image forming conditions to suppress the uneven density in solid images. The control tables are generated for the photoconductor drum and developing roller respectively. Then, the low density image pattern is formed and detected. This pattern is formed while applying the modulation of the developing bias. After that, the control tables for the charging bias $V_c(t)$ are calculated and determined in almost the same way as those for $V_b(t)$. The control biases $V_b(t)$ and $V_c(t)$ are approximated by sine curves expressed as follows:

$$V_b(t) = V_b + A_{bp} \cdot \sin(\omega_p \cdot t + \theta_{bp}) + A_{bd} \cdot \sin(\omega_d \cdot t + \theta_{bd}) \quad (1)$$

$$V_c(t) = V_c + A_{cp} \cdot \sin(\omega_p \cdot t + \theta_{cp}) + A_{cd} \cdot \sin(\omega_d \cdot t + \theta_{cd}) \quad (2)$$

where V_b / V_c are constant developing and charging biases determined from process control, A_{bp} / A_{cp}, A_{bd} / A_{cd}, θ_{bp} / θ_{cp}, and θ_{bd} / θ_{cd} are control parameters to modulate for the photoconductor drum and development roller, and ω_p / ω_d are the angular velocity of the photoconductor drum and the development roller.

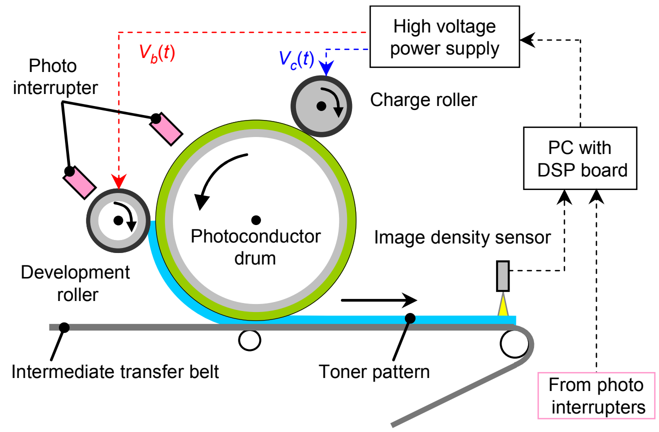


Figure 5. Experimental setup

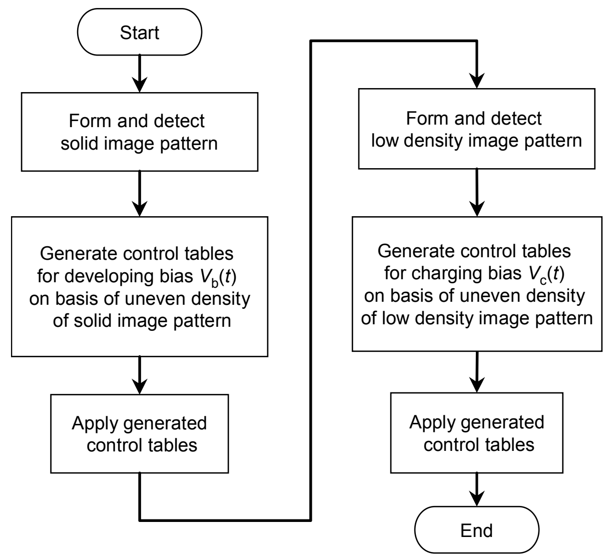


Figure 6. Schematic flowchart of control for suppressing uneven density

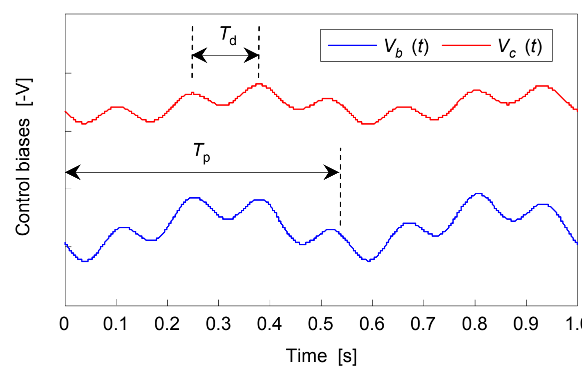
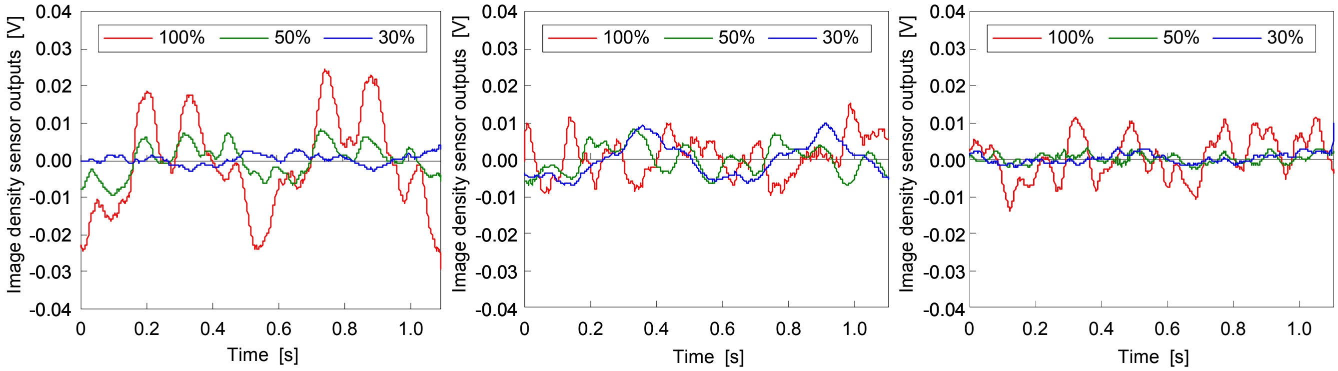


Figure 7. Waveforms of control biases

After determining the control parameters in the above steps, the two controlled biases $V_b(t)$ and $V_c(t)$ are periodically changed as shown in Figure 7, where T_p and T_d mean the periods of the photoconductor drum and development roller.



(a) *Without control* **(b)** *Previous method* **(c)** *Proposed method*

Figure 8*. Experimental results for density unevenness under various densities*

Experimental Results

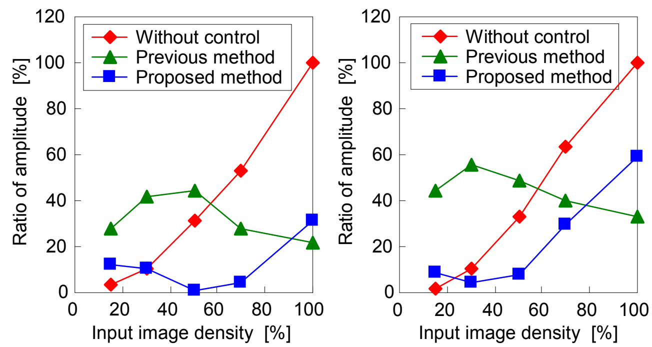
In our new method for improving the periodic density unevenness, the biases V_c and V_b were determined by process control, and other control parameters were determined by a method for identifying the control effects for various densities.

To evaluate the new method, we compared experimental results for density unevenness obtained with it with results obtained with the previous method. All of the experiments were carried out under identical image forming conditions and repeated several times to confirm measurement repeatability. The density unevenness was evaluated using the outputs of the image density sensor on the intermediate transfer belt.

Figure 8 shows the experimental results for density unevenness under various image densities: 100%, 50%, and 30%. Figure 8(a), (b), and (c) show the results obtained without control, with the previous method, and with the new method, respectively. As can be seen in (b), the previous method can successfully reduce the density unevenness under 100% density, but it increases the unevenness under 30% density. It would appear that with this method the developing bias control causes imbalance of the development field in low density images. As can be seen in (c), however, the new method successfully reduces the density unevenness in a broad density range. It is particularly noteworthy that the unevenness under 30% density in (b) was suppressed by controlling the charging bias. In the figure, the fluctuation at 100% in (b) and (c) is a non-periodic component caused by the development process, and it is not adversely affected by the control.

Figure 9(a) and (b) show a comparison of the amplitudes of periodic density unevenness in the image data. These amplitudes were calculated from image density sensor outputs by using FFT, and all data was normalized to that for “100% without control”. From the figure, we can see that the previous method causes periodic density unevenness under low density. In particular, in the 30-50% range the periodic density unevenness becomes higher than it had been without control. The new method, however, effectively improves the periodic density unevenness in a broad density range.

Figure 10 graphs the improvement level shown in Figure 9. It shows that the new method reduces the periodic density unevenness by about 40% to 70% in solid images, and that control effects are obtained with it in the range over 30%.



(a) *For photoconductor drum* **(b)** *For development roller*

Figure 9*. Comparison of the amplitudes of density unevenness*

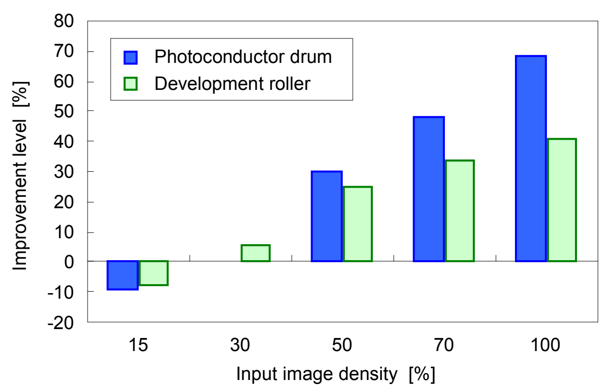


Figure 10*. Improvement level using proposed method*

In the range under 30%, the amplitude became larger than it had been without control, but this has little or no impact on the visible image quality.

The results we have obtained confirm that our proposed method effectively improves the periodic density unevenness in a broad density range, solves the problems that occurred with the previous method, and enables high quality print images to be obtained without using any high-precision components.

Conclusions

This paper described a new method we developed for improving periodic density unevenness in images. We conducted experiments to thoroughly investigate the improvement in periodic density unevenness obtained with the method and measured the method’s performance under various densities. The following conclusions were obtained:

1. The density unevenness is affected very little by the post-development processes.
2. The eccentric rotation of the photoconductor drum and development roller is the major cause of the periodic density unevenness.
3. The periodic density unevenness arises from the fluctuation of the developing gap caused by the eccentric rotation.
4. The new method effectively improves the periodic density unevenness caused by the eccentric rotation of the photoconductor drum and the development roller in a broad density range.

Our new method solves the problems occurring with the previous method and enables high quality print images to be obtained without using any high-precision manufacturing components. The method has the potential to help electrophotographic printers produce high quality images and accelerate their entry into the production printing market.

References

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Author Biography

Satoshi Kaneko received his A. Eng. from Oyama National College of Technology (2004), his B. Eng. from Gunma University (2006), his M. Eng. from Tokyo University of Agriculture and Technology (2008) in Mechanical Engineering, and entered Ricoh Company, Ltd. Since then he has worked in the Imaging Engine Development Division, and engaged in the development and design of process control for electrophotographic printers.