CORRECTION OF THE COLOR REGISTRATION ERROR THROUGH ADJUSTMENT OF INSTALLATION PHASES OF GEARS WITH RUNOUT

Mun-Bo Shim and Soo-Yong Kim; Samsung Electronics Co., Ltd.; Suwon, Gyeonggi/Korea

ABSTRACT

In this paper, a new method is proposed for correcting the AC component of the color registration error in the paper feeding direction in a tandem-type color laser printer. The main factor of the AC color registration error which is the vibration in low frequency band is the fluctuation of the angular velocity of organic photoconductive (OPC) drums caused by gears with runout in multiple gear systems. In order to express the fluctuation of the angular velocity of OPC drums, the kinematical relation between a pair of gears with runout is constructed and it is extended into a multiple gear system. Also, the specific reduction ratio in the multiple gear system is proposed as a necessary condition for the correction of the AC color registration error. With the AC color registration error obtained by integrating the angular velocity of each drum, the minimization problem is formulated in term of the installation phase of the gears with runout. A continuous evolutionary algorithm is used to find the optimal installation phases. A comparison between simulation results and experimental ones demonstrates the feasibility and effectiveness of the proposed method.

Introduction

The market demand for high-speed performance of a color laser beam printer created a tandem-type color printers which have four organic photoconductive (OPC) drums to develop four colors (Cyan, Magenta, Yellow, and Black). While the conventional system with one drum uses four cycle process to create a full color image, the tandem can produce the image just with one cycle process. In spite of its efficiency and high speed, it produces a problem of color registration which did not occur in the one drum system. Color registration error is generally defined as the difference of the position among four color lines/dots on the printed images. It occurs along the laser scanning direction and paper feeding direction. It also consists of the fluctuation of the registration error (the AC component) and the average error (the DC component).

Fig. 1 shows various examples of the DC component of the color registration error. It is well known that the registration error along the laser scanning direction can be corrected electrically and the correction of the DC component of the registration error is mainly performed by the electrical and optical system of the laser scan unit (LSU). [1, 2, 3]

The position variation which is defined as the difference between regular (or ideal) position and printed one on the image becomes the AC component of the color registration along the paper feeding direction as shown in Fig. 2. It is mainly induced by the fluctuation of the angular velocity of OPC drums. [4]

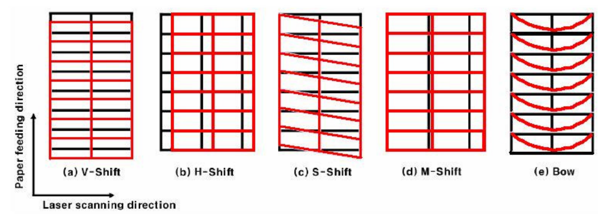

Figure 1. *Examples of DC component of color registration error*

The fluctuation is quite related to a multiple gear system including gears with runout. For a cost merit, the drums are generally driven by one motor through the gear system. If the four OPC drums each are driven by gears with runout, each drum will have different fluctuations in its surface velocity. Owing to the fluctuations, the images on the OPC drums are not developed regularly in space even under the constant scanning interval of laser units. After transferring to paper occurs, the image brought by the velocity fluctuations is shown in Fig. 2.

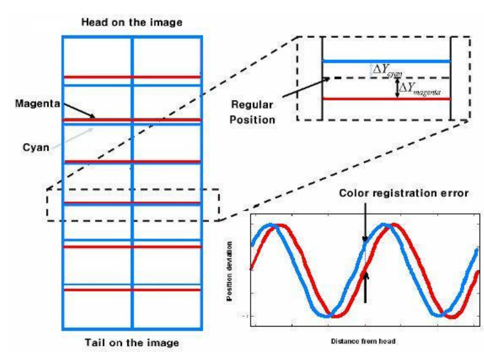

Figure 2*. AC component of color registration error expressed by the position variation.*

The correction of the AC component as well as the relation between the color registration error and the fluctuation caused by gears with runout has never been reported in the mechanical point of view. Similar to the correction of a DC component, it may be performed through the optical system based on feedback control.

In this paper, the AC component of the color registration error in the paper feeding direction is corrected through the adjustment of the installation phases of gears with runout. The fluctuation of the angular velocity of OPC drums is mainly caused by gears with runout in the driving unit. In order to express the fluctuation, the kinematical relation between a pair of gears with runout is constructed and it is extended into a multiple gear system. With the AC color registration error obtained by integrating the angular velocity of each drum, the minimization problem is formulated in term of the installation phase of the gears with runout. A continuous evolutionary algorithm (CEA)[5, 6] which is studied in the previous study is used to find the optimal installation phases of the gears. However, the system will require some additional sensors/processors and the product cost will increase. Owing to the structure driven by one motor through the gear system, it is not sure whether the correction is easy to achieve or not.

Problem statement

Since four OPC drums are driven by one motor and the gears in the driving system have runout, the angular velocity of each drum is fluctuated without any treatment such as an additional control system or use of precise gears which does not prove meaningfully from the economic point of view. The fluctuation generates the AC component of the color registration error between exposures to transferring in electro photographic (EP) printing. Assuming that the exposure by the LSU is done in time and there is no slip transferring, the position of a dot on the image can be obtained by integrating the linear velocity of a drum at a transfer point. The difference of the positions generated by four colors becomes the color registration error.

The purpose of this study is to correct the AC component of the color registration error in the paper feeding direction through the adjustment of the installation phases of gears with runout. The AC component is caused by the position variation of four colors. The problem of this correction can be stated as:

Minimize:

$$f(e_i, \varphi_i) = \max(\Delta Y_{yellow}, \Delta Y_{magenta}, \Delta Y_{cyan}, \Delta Y_{black}) - \min(\Delta Y_{yellow}, \Delta Y_{magenta}, \Delta Y_{cyan}, \Delta Y_{black}) \quad \textbf{(1)}$$

Where e is gear's runout or eccentricity, φ is the installation phase of the gear, and i is the number of gears of interest. According to Eq. (1), the correction of the AC component means the synchronization of the position variation of four colors on the image. The range of the installation phase is within 2π. A continuous evolutionary algorithm is used to find the optimal installation phases of the gears.

In advance of obtaining the optimal installation phases, the specific reduction ratio of the gears must be determined in a multiple gear system. If the angular velocity of each drum changes with the different period, it is sometimes impossible to synchronize the position variation of four colors. Therefore, the proper reduction ratio, that is, the number of teeth of gears is determined before correcting the color registration error.

Correction of color registration error

The correction of AC component of the color registration error in the paper feeding direction is to find the installation phases of gears with runout that minimize the position variation generated by four colors OPC drums connected with a multiple gear system. This section presents technical details of the proposed method: (1) reduction ratio for synchronization, (2) kinematical relation between a pair of gears with runout, and (3) continuous evolutionary algorithm.

Reduction ratio for synchronization

The synchronization is an important design consideration in tandem-type color printers. In order to synchronize the position variation of four colors on the image, the time when the paper travels from one color transfer point to the next, what we call, OPC.

In the tandem color laser printer. Let L be the OPC pitch and d_{drum} be the diameter of a drum. Assuming that the paper slip may be neglected, the process velocity of the paper can generally be expressed as

$$V_{paper} = V_{opc} = \frac{d_{drum} \times \omega_{opc}}{2} \quad (2)$$

Where ω_{opc} is the angular velocity of a drum and V_{opc} is the linear velocity of the drum at a transfer point. To synchronize the position variation of four colors on the images,

$$\frac{\Delta t}{T} = \frac{L / V_{opc}}{2\pi / \omega_{opc} R_j} \cong k \quad (3)$$

must be satisfied. Where Δt is the time the paper travels the OPC pitch in and T is the period of a drum. R_j is the reduction ratio from j -th gear in the multiple gear system to a OPC coupling one and k is an integer. Eq. (3) can be rewritten as.

$$\frac{L}{\pi d_{drum}} \cdot \frac{1}{R_j} \cong k \quad (4)$$

Generally, the reduction ratio in the gear system is determined, depending on the design specification. However, if the number of teeth of the gears each in the multiple gear system is modified based on Eq. (4) without any change or with a small change of the entire reduction ratio, a necessary condition for the synchronization of the position variation can be reached.

Kinematical relation between a pair of gears with runout

The color registration error caused by a gear system is the vibration in low frequency band. The gear dynamics literature includes a large number of dynamics models which are aimed at predicting dynamic characteristics of gear systems. [7, 8, 9, 10] However, there are a few studies on the transmission deviation caused by gears with runout in low frequency band. [11, 12] Besides they regard the runout as an eccentricity without considering the actual runout profile. In this paper, the kinematical relation between a pair of gears with runout, namely, the fluctuation of the angular velocity is established based on the position deviation on the line of action. Since it is obtained by assuming that the runout of the gear is sinusoidal, it is easily updated with the actual runout profile via the Fourier series. The transmission deviation is obtained by integrating the fluctuation of the angular velocity and the color registration error is expressed in term of the installation phase of the gears with runout.

To calculate the fluctuation of the angular velocity of OPC drums in the multiple gear system, a mathematical expression between a pair of gears with runout is derived. In Fig. 3, there are the driving and driven gears, respectively. For simplicity, only one has runout and the other is perfect. Let O_1, O_2 be the centers of rotation of the gears and r_{b1}, r_{b2} be their base radii.

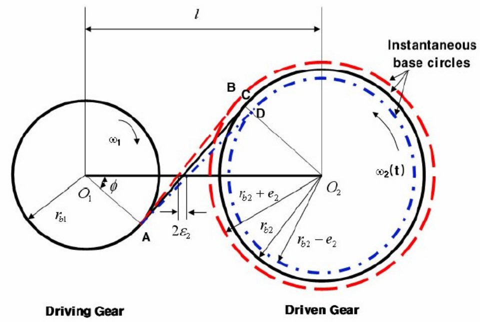

Figure 3. *Geometrical configuration of the mesh of a perfect pinion and a gear with runout.*

Assuming that the runout of the driven gear is sinusoidal as shown in Fig. 4, the base radius instantaneously ranges from $r_{b2}-e_2$ to $r_{b2}+e_2$, where e_2 is the amplitude of the runout in rolling chart, what we call eccentricity.

The change of the base radius of the driven gear causes the variation of the pitch point whose the peak-to-peak amplitude is $2\varepsilon_2$. Therefore, the fluctuation of the angular velocity of the driven gear under the constant angular velocity of the driving gear can be obtained as:

$$\omega_2(t)=\frac{r_{p1}-\varepsilon_2\cdot\sin(\omega_1\cdot t/R+\varphi_2)}{r_{p2}+\varepsilon_2\cdot\sin(\omega_1\cdot t/R+\varphi_2)}\cdot\omega_1 \tag{5}$$

Where r_{p1}, r_{p2} are the radii or the pitch circles and R is the reduction radio. φ_2 is the installation phase relative to a datum point where the runout is measured.

The variation of the pitch point expressed in term of the runout is derived from the observation of the movement of the line of action as depicted in Fig. 5.

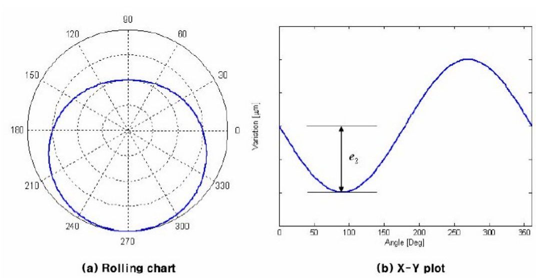

Figure 4. *Rolling chart and X-Y plot of runout.*

Let F be the pitch point when there is no runout in a gear system and E, G be the intersecting points of the center distance ($\overline{O_1O_2}$) and the lines of action. The variation of the pitch point is equal to the summation of the lines EF and FG.

First, the Law of Sines is applied to the triangle ΔO_1AF in order to obtain $\overline{EF}$ within the variation of the pitch point.

$$\frac{r_{p1}-\overline{EF}}{\sin(\pi/2-\alpha)}=\frac{r_{b1}}{\sin(\pi/2-\alpha-\phi)} \tag{6}$$

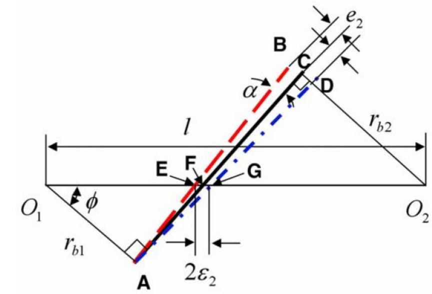

Figure 5. *Variation of the pitch point by a gear with runout.*

Where α is the angle $\angle BAC$ generated by the movement of the line of action and ϕ is the pressure angle. Although the line of action through the pitch point E does not pass the point A exactly, the discordance is too small to neglect. Eq. (6) implies

$$\overline{EF}=r_{p1}-\frac{r_{b1}}{\cos\phi+\sin\phi\tan\alpha} \tag{7}$$

where

$$\cos\phi=\frac{r_{b1}+r_{b2}}{l},\quad \sin\phi=\frac{\sqrt{l^2+(r_{b1}{}^2+r_{b2}{}^2)^2}}{l},\quad \tan\alpha=\frac{e_2}{\sqrt{l^2-(r_{b1}{}^2+r_{b2}{}^2)^2}}. \tag{8}$$

Substituting Eq. (8) into Eq. (7), the line $\overline{EF}$ becomes

$$\overline{EF}=r_{p1}-\frac{l\times r_{b1}}{r_{b1}+r_{b2}+e_2} \tag{9}$$

The remaining of the variation of the pitch point $\overline{FG}$ is determined in the same manner.

$$\overline{FG}=-r_{p1}+\frac{l\cdot r_{b1}}{r_{b1}+r_{b2}-e_2} \tag{10}$$

Finally, the variation of the pitch point expressed in term of the runout is

$$\varepsilon_2=\frac{l\cdot e_2\cdot r_{b1}}{(r_{b1}+r_{b2})^2-e_2{}^2} \tag{11}$$

According to the above procedure, the fluctuation of the angular velocity of the driven gear in a pair of gears with runout can be obtained by linear superposition of the variation of the pitch point expressed in term of the runout.

$$\omega_2(t)=\frac{r_{p1}+\varepsilon_1\cdot\sin(\omega_1\cdot t+\varphi_1)-\varepsilon_2\cdot\sin(\omega_1\cdot t/R+\varphi_2)}{r_{p2}-\varepsilon_1\cdot\sin(\omega_1\cdot t+\varphi_1)+\varepsilon_2\cdot\sin(\omega_1\cdot t/R+\varphi_2)}\cdot\omega_1 \tag{12}$$

In addition, it is extended into a multiple gear system to express the fluctuation of the angular velocity of OPC drums. At that time, a gear drives an adjacent one with phase lag/lead of the runout simultaneously when it is driven.

The positions of dots on the image can be obtained by integrating the linear velocity of an OPC drum, respectively. The change of an OPC drum in the radial direction is ignorable since the diameter of a drum is far greater than the change of the radius of the coupling gear. In addition, the angular velocity caused by the actual runout profile can be obtained by modifying Eq. (5) after the profile is represented approximately by the Fourier series.

Continuous evolutionary algorithms

Evolutionary algorithms (EAs) are probabilistic optimization algorithm based on the model of natural evolution and the algorithm has clearly demonstrated its capability to create good approximate solutions in complex optimization problems. Continuous evolutionary algorithms (CEAs) [5, 6, 13] are one set of EAs, which is specifically formulated for the optimization with continuous search space. The reproductive operations of CEAs are intended to be similar to those of genetic algorithms (GAs) such that it can take the advantage of probabilistic features in GAs. The major difference of CEAs from GAs is that a search point itself, i.e. a real continuous vector, gives the representation of the individual. First, a population of individuals, each represented by a continuous vector, is initially (generation *n=0*) generated at random, i.e.

$$P^n = \{x_1{}^n, ..., x_\lambda{}^n\} \qquad (13)$$

Where x represents the vector of real variables and λ is the number of parental individuals in the problem.

The definition of the recombination and mutation becomes the probabilistic distribution of the phenomenological measures accordingly. The recombination operation is then defined as

$$\begin{aligned} x_a^{n+1} &= (1-\mu_a^n)x_a^n + \mu_b^n x_b^n \\ x_b^{n+1} &= \mu_a^n x_a^n + (1-\mu_b^n)x_b^n \end{aligned} \qquad (14)$$

where x_a^n, x_b^n , are parental individuals at generation n and parameter $\mu_i^n \ \forall i \in \{a,b\}$ may be defined by the normal distribution with mean 0 and standard deviation σ

$$\mu_i^n = \text{gauss}(0,\sigma^2) \qquad (15)$$

The mutation can also be achieved simply by implementing

$$x^{n+1} = \text{rand}(x_{min}, x_{max}) \qquad (16)$$

The evaluation of the fitness can be conducted with a linear scaling, where the fitness of each individual is calculated as the worst individual of the population subtracted from its objective function value

$$\Phi(x_i^n) = \max\{f(x^n) \mid x^n \in P^n)\} - f(x^n), \ \forall i \in \{1,...,\lambda\} \qquad (17)$$

Proportional selection which is the most popular selection operation in GAs [14, 15] also is directly used in CEAs. Optionally, ranking selection can be implemented in this algorithm. These reproductive operations form one generation of the evolutionary process which corresponds to one iteration in the algorithm. The iteration is repeated until a given terminal criterion is satisfied.

Results and discussion

Some case studies have been performed to verify the effectiveness of the proposed methodology. A multiple gear system shown in Fig. 6 was used for the correction of the AC component of the color registration error. In this system, the OPC drum pitch is 54mm and the diameter of a drum is 24mm. Provided that the angular velocity of a motor pinion is constant, the reduction ratio from first idle gear to a coupling gear one by one is considered to satisfy a necessary condition for the synchronization. According to Eq. (4), the k values in the multiple gear system become 1.3, 0.6, 1.3, and 1.3 which are not close to an integer.

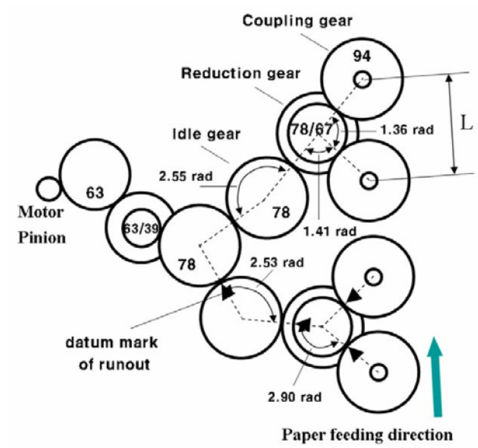

Figure 6. *Multiple gear system driving OPC drums.*

Owing to the inadequate reduction ratio, the runout of all gears may affect the AC component of the color registration error badly. In this study, we considered that 8 gears marked in Fig. 6 had runout.

Assuming that the runout of the gears is sinusoidal and the peak-to-peak amplitude is 30, it is expressed from the datum mark as shown in Fig. 7. The correction of the AC color registration error to be formulated was defined as Eq. (1) and the design variables were the installation phases of 8 gears with runout. CEAs for this study are set up: population size is 30; standard deviation is 0.5; mutation rate is 0.01. Also, proportional selection method is adopted for the selection process. The iteration is repeated until the generation reaches 50.

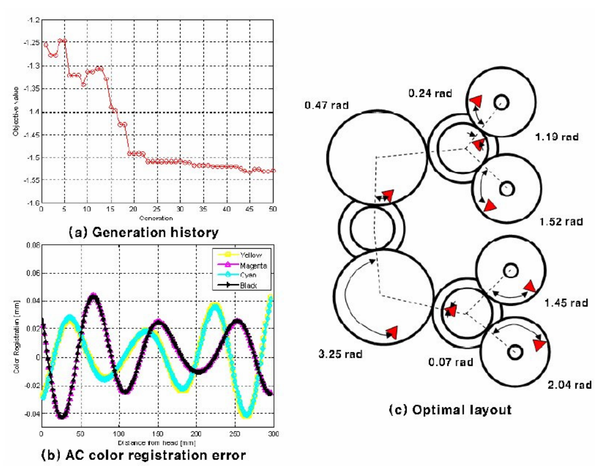

Figure 7. *Correction of AC color registration error.*

Fig. 7 illustrates the result of the correction of the AC color registration error. Fig. 7 (a) and (b) show the convergence history of the objective function and the AC color registration error in adopting the installation phases in Fig. 7 (c) to the multiple gear system. The AC color registration error generated in this system cannot be corrected due to the inadequate reduction ratio.

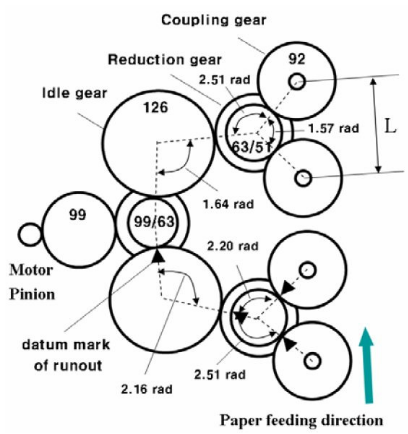

***Figure 8**. Improved multiple gear system.*

To tackle the problem of the above system, a multiple gear system shown in Fig. 8 was improved based on Eq. (4) under the physical constraints. The k values in new gear system become 1.01, 1.01, 1.01, 2.01, and 2.01 to satisfy a necessary condition for the synchronization.

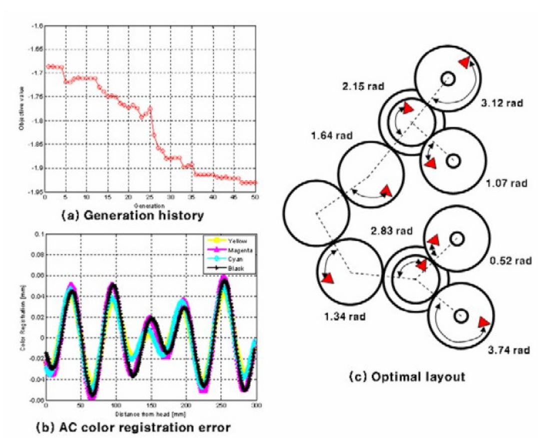

***Figure 9**. Correction of AC color registration error in improved multiple gear system.*

Fig. 9 illustrates the result of the correction of the AC color registration error in the improved multiple gear system. Fig. 9 (a) and (b) show the convergence history of the objective function and the AC color registration error in adopting the installation phases in Fig. 9 (c). We found out that the AC color registration error could be completely removed thanks to the reduction ratio of the improved multiple gear system. Even if the remaining gears had runout under the optimal installation phases of 8 gears with runout and were installed randomly, the position variation of each color was synchronized as shown in Fig. 10. In both cases, their runout is sinusoidal and the peak-to-peak amplitude is 30.

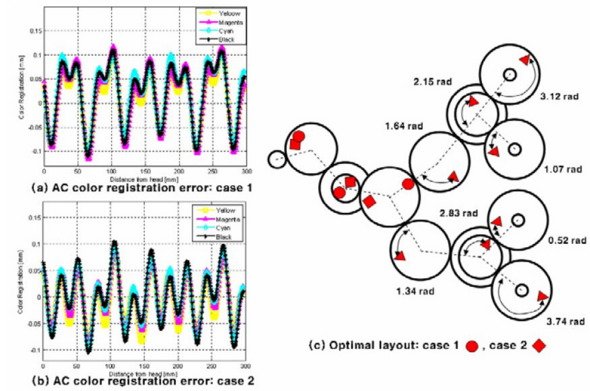

***Figure 10.** AC color registration error in having the remaining gears with runout installed randomly.*

The proposed methodology was actually applied to the tandem color laser and the effectiveness was verified experimentally. Since the optimal installation phases in the above cases study are obtained on the assumption that the runout profile is sinusoidal, an actual profile of the runout is required to find out the practical installation phases. Actually runout profiles of gears are generally different from the ideal one because of their injection molding conditions and a gate position etc.

However, if they can be represented approximately by the Fourier series, the fluctuation of the angular velocity of the gears can be obtained by substituting the even and odd Fourier coefficients into Eq. (11). Fig. 11 illustrates the optimal installation phases for the correction of the AC color registration error and the comparison between the simulation result and the experimental one.

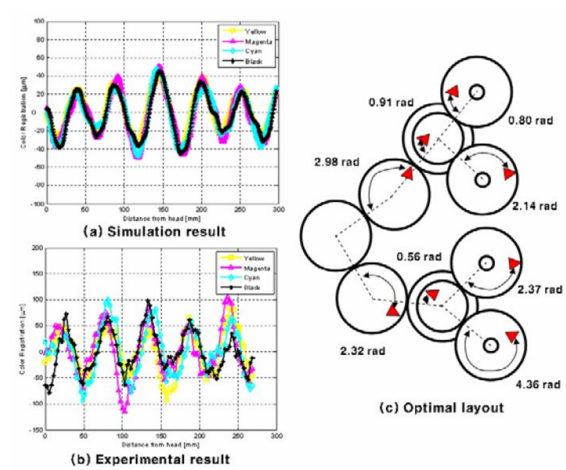

***Figure 11.** Correction of AC color registration error and comparison between the simulation result and the experimental one.*

The experimentally obtained result is quite similar to the simulation one and the period length of their position variation corresponds to OPC drum pitch (54 mm) owing to the proposed reduction ratio based on Eq. (3). The difference of their amplitude appears but it is caused by the remaining gears with runout as shown in Fig. 11. Fig. 12 shows AC color registration error on a page.

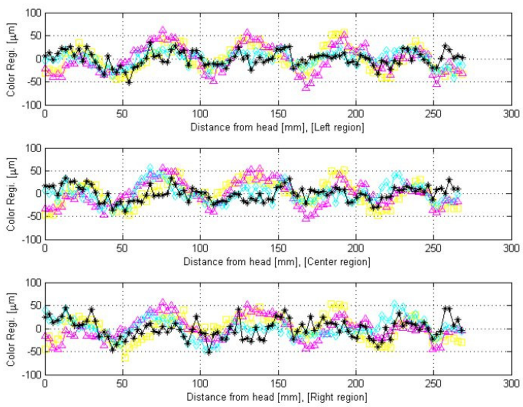

Figure 12. *AC color registration error on a page.*

Conclusion

The AC component of the color registration error in the paper feeding direction was corrected through the adjustment of the installation phases of gears with runout. The fluctuation of the angular velocity of OPC drums was considered as a key factor for the AC color registration error and it was mainly caused by gears with runout in the driving system. In order to express it, the kinematical relation between a pair of gears with runout was constructed and it was extended into a multiple gear system. Also, the specific reduction ratio in the multiple gear system was proposed as a necessary condition for the correction of the AC color registration error. With the AC color registration error obtained by integrating the angular velocity of each drum, the minimization problem was formulated in term of the installation phase of the gears with runout. A continuous evolutionary algorithm (CEA) was used to find the optimal installation phases.

Both simulation results and experimental ones were presented to demonstrate the feasibility and effectiveness of the proposed methodology. From the case studies, it was found out that the multiple gear system should be developed based on the reduction ratio for the correction of the AC color registration error. The comparison between two results showed that our approach synchronized very well the position variation of four colors due to the fluctuation of the angular velocity of OPC drums.

References

[1] V. Castelli, J. deJong, L. Williams, A strategy for tandem color registraion, Proceedings of SPIE -- Volume 2658 Color Imaging: Device-Independent Color, Color Hard Copy, and Graphic Arts, San Jose, CA, January 1996, pp. 96-104.

[2] K. Sakai, A technical overview of optical unit for tandem color laser printer, Proceedings of the IS&T's NIP22:International Conference on Digital Printing Technologies, Denver, CO, September 2006, pp. 568-571.

[3] A. Yoshizawa, Registration control of four-color images for high-speed color copier, Proceedings of SPIE -- Volume 2658 Color Imaging: Device-Independent Color, Color Hard Copy, and Graphic Arts, San Jose, CA, January 1996, pp. 105-111.

[4] K. Asakura, M. Yoshikawa, M. Aizawa, N. Tajima, Color laser printer: Color registration by QLPT mechanism, Proceedings of the IS&T's NIP15: International Conference on Digital Printing Technologies, Orlando, FL, Octocber 1999, pp. 604-607.

[5] M.-B. Shim, T. Furukawa, S. Yoshimura, G. Yagawa, M.-W. Suh, Pareto-based continuous evolutionary algorithms for multiobjective optimization. Engineering Computations: International Journal for Computer-Aided Engineering and Software 19 (1) (2002) 22-48.

[6] M. B. Shim, M.W. Suh, Crack identification using evolutionary algorithms in parallel computing environment. Journal of Sound and Vibration 262 (2003) 141-160.

[7] H. Iida, A. Tamura, H. Yamamoto, Dynamic characteristics of a gear train system with softly supported shafts, Bulletin of the Japan Society of Mechanical Engineers 29 (252) (1986) 1811-1816.

[8] A. Kahraman, R. Singh, Non-linear dynamics of a spur gear pair, Journal of sound and vibration 142 (1) (1990) 49-75.

[9] A. Kahraman, Dynamic analysis of a multi-mesh helical gear train, Transactions of the ASME 116 (1994) 706-712.

[10] T. Oiwa, O. Yoshida, In-process Measurement for Gear Eccentricity, Journal of Japanese Society Precision Engineering 68 (2)□2002□244-247 (in Japanese) .

[11] T. Kusuda, M. Ikeda, T Ogiri, T Besshi, Transmission deviation caused by eccentricity in multi gear systems, IS&T's PICS 1999:Image Processing, Image Qualtiy, Image Capture, Systems Conference, Savannah, GA, April 1999, pp. 119-124.

[12] H. N. HZGPVEN, D. R. HOUSER, Mathematical models used in gear dynamics-a review, Journal of Sound and Vibration 121 (1988) 383-411.

[13] T. Furukawa, G. Yagawa, Inelastic constitutive parameter identification using an evolutionary algorithm with continuous individuals, International Journal for Numerical Methods in Engineering 40 (1997) 1071-1090.

[14] D. Goldberg, Genetic Algorithms in Search, Optimization and Machine Learning, Addison-Wesley, Reading, MA, 1989.

[15] M.-W. Suh, M.B. Shim, M.Y. Shim, Crack identification using hybrid neuro-genetic technique, Journal of Sound and Vibration 238 (2000) 617-635.

Author Biography

Sooyong Kim received his B.S., M.S. and Ph.D degree in Department of Mechanical Engineering from Sungkyunkwan University, Suwon, Korea,in 1994, 1996 and 2001. He spent 3 years as a Post-Doctral Fellow in the Department of Mechanical Engineering of Tokyo University. Since 2003 he has joined the Printig Division of SAMSUNG ELECTRONICS, Co.LTD. His main research interests include motion quality of printing devices.