Journal of Imaging Science and Technology® 56(2): 020502-1–020502-11, 2012.

Experimental Characterization of Transient Tone Deviation in Print Jobs for Color Electrophotography[1]

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Abstract. *Print quality tests using off-the-shelf color electrophotographic printers revealed systematic tone fluctuations among the first several pages in print jobs after idle periods as short as 1 min, under certain environmental conditions. It can be shown that the tone values on the first few pages of a print job after 1 min of idle are statistically different from the tone values on the other pages of the same job. In the mid-tone ranges, the mean tone value difference between pages can differ by 4 ΔE_{76} units under low temperature and low humidity conditions. This article presents an experimental approach to characterize this type of transient tone deviation in a print job for tone consistency control and improvement. A first-order difference model is employed to approximate the transient tone deviation. The resulting model can accurately predict the transient tone deviation over pages to within 1.3 ΔE_{76} units, based on cross-validation. © 2012 Society for Imaging Science and Technology.*
[DOI: 10.2352/J.ImagingSci.Technol.2012.56.2.020502]

INTRODUCTION

A color electrophotographic (EP) printing system typically uses four primary colorants—cyan, magenta, yellow, and black. Tone values of the primary colorants are the measured densities of color patches reproduced on output media. Consistent tone reproduction is desired in color EP printers. This study characterizes tone deviation between pages in print jobs after a short idle period.

Print quality (PQ) tests are commonly performed to examine tone reproduction consistency of color EP printers. In a typical PQ test, pages containing primary color patches at a set of predetermined halftone levels are printed. The corresponding tone values are measured by an off-line device, such as a spectrophotometer; and the results are analyzed to ensure that the design specification of the printers is met, and sufficiently reliable performance is attained. In this study, a tone value is defined as the Euclidean distance (ΔE) in CIE $L^*a^*b^*$ space[1] between the measured color of a primary color patch printed at a specific halftone level, and the substrate (media) color. A halftone level is represented by a unit-less 8-bit integer, where 0 represents no colorant and 255 represents the maximum amount of colorant to be deposited on media.

Print quality tests reveal tone fluctuation with several color EP printers of the same model under certain environmental conditions. In these tests, the printers are operating under controlled environmental conditions. A print job consisting of 200 pages is printed with constant EP control parameters, e.g., developer bias voltages, and is repeated three times. In each print job, test pages with primary color

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Received Oct. 31, 2011; accepted for publication Apr. 17, 2012; published online May 18, 2012

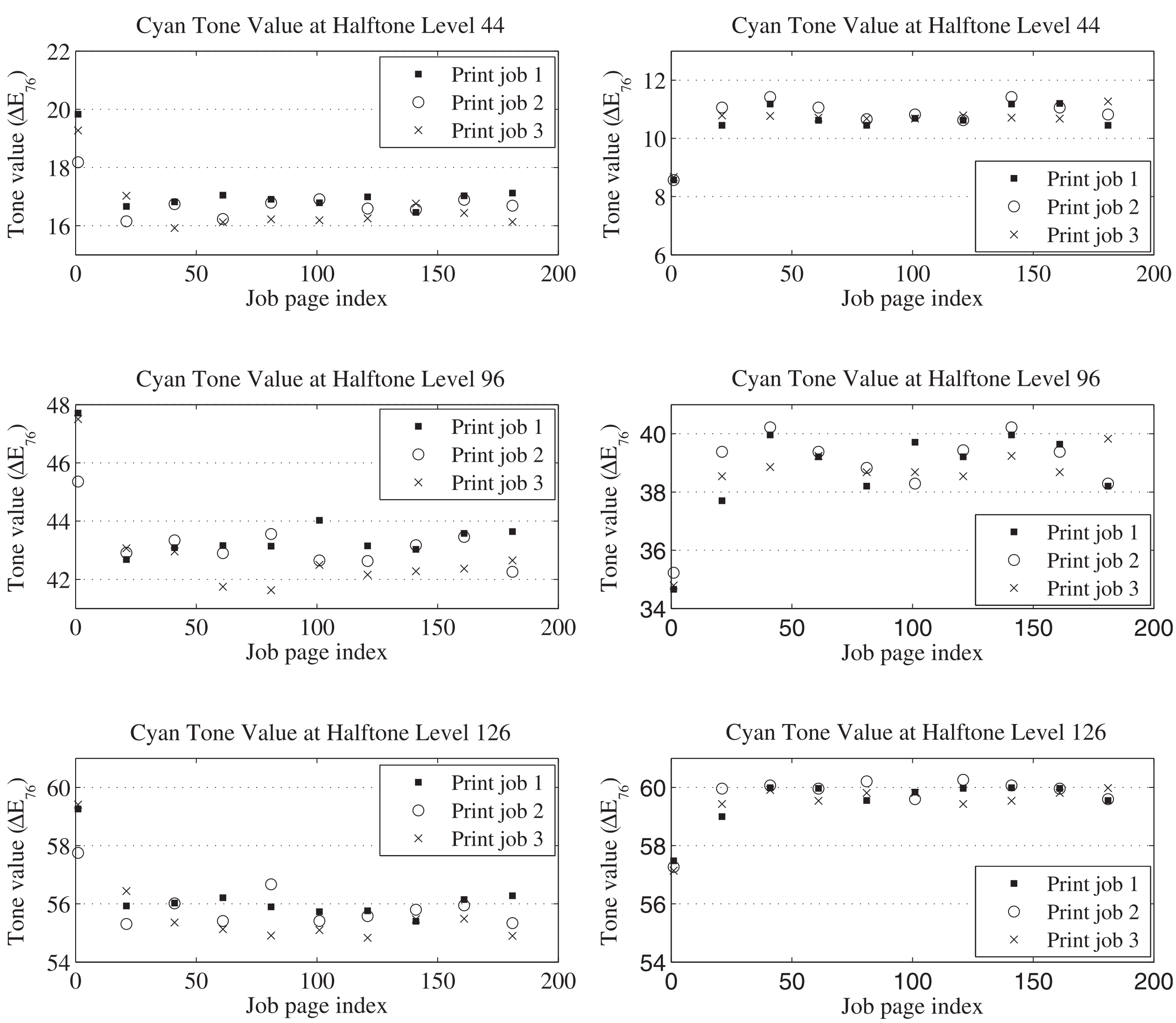
1062-3701/2012/56(2)/020502/11/$20.00.

[1]Research supported by the Hewlett-Packard Company. Research partially conducted while Yan-Fu Kuo and Chao-Lung Yang were graduate students at Purdue University. Carl D. Geleynse was an employee of Hewlett-Packard Company, Boise, ID when this work was performed.

patches are placed 20 pages apart, starting from the first page. The rest of the pages are chosen from a variety of sample text and graphic images with coverage ranging from approximately 5% to 20%. The pages in a job are printed continuously; but a break of a few minutes is inserted between jobs. The tone values of the test pages are plotted according to the sequence of the corresponding job page indices (see Figure 1).

Fig. 1 shows the cyan tone values at three different halftone levels from three print jobs for two off-the-shelf in-line color EP printers of the same model. The printer model employs indirect transfer technology at a throughput of 30 pages-per-minute (ppm) with a native resolution of 600 dots-per-inch (dpi). The tests are performed under (a) 15°C and 10% relative humidity (RH) and (b) 30°C and 80% RH environmental conditions, respectively. Fig. 1(a) shows that the tone values of the first pages are consistently larger than the tone values of all the other pages under the 15°C and 10% RH condition. Their mean tone value differences are especially large in the mid-tone range, e.g., as large as 4.0 ΔE_{76} units at halftone level 96. Fig. 1(b) shows that the tone values of the first pages are consistently smaller than the tone values of all the other pages under the 30°C and 80% RH condition. Their mean tone value differences can be as large as 4.2 ΔE_{76} units at halftone level 96. These tone value differences are larger than human visual threshold and can be perceived by observers.

Tone variation in color EP has been studied. The majority of the works focus on long-term color discrepancy due to changes in environmental conditions or consumable factors, such as temperature, humidity, or organic photoconductor (OPR) drum life.[2–7] In those works, long-time scale tone variation was observed and modeled as a static function of environmental and consumable conditions. Other studies[8–10] have looked into color variation over time due to toner aging for a two-component development system. In



(a) (b)

Figure 1. Cyan tone values of the print quality experiment at halftone levels 44, 96, and 126 under (a) 10°C and 15% relative humidity, and (b) 30°C and 80% relative humidity environmental conditions.

these works, the effect of toner aging on color consistency is gradual and the effective time constant is in tens of minutes. In contrast, the transient tone fluctuation observed in Fig. 1 appears immediately after a print job starts while the printer operates under fixed consumable and environmental conditions. Regression analysis shows that its time constant is in seconds. This type of short-term transient tone fluctuation has received little attention in the literature.

The short-term transient tone fluctuation shown in Fig. 1 can be viewed as a transient response of the EP process. The start and stop of a print job change the physical state of each of the EP subsystems. Changes, such as the tribo-charging of the toner, the status of the toner on the development subsystem, the electric field configurations in the transfer nips, and even the media transport conditions, lead to differences during charging, exposure, development, and transfer. The dynamic responses of these subsystems are not instantaneous and are different in various environmental conditions and thus may result in a transient behavior of the tone reproduction. While the exact cause is unknown, this phenomenon characterizes the coupled effect of many subsystems in the EP process. In this study, we focus on characterizing this type of transient tone deviation.

It is important to characterize transient tone deviation associated with short time constants for EP systems. This type of tone deviation is associated with relatively fast dynamics so that it cannot be compensated by typical measurement-based calibration approaches.[11–13] Instead, the tone deviation should be mitigated using model-based compensation strategies. In these strategies, models are developed to predict the transient tone deviation so that appropriate tone correction mapping or EP control parameters can be adjusted page by page to compensate for the tone deviation. The accuracy of the model is crucial since the compensation has to run in an open-loop mode, where on-line measurement of the resulting tone value is typically not available.

This study characterizes the transient tone deviation in a print job as a system-level phenomenon for color EP systems. A first-order difference model is employed to approximate the tone deviation with halftone level and job page index as model variables. The resulting model can accurately predict the transient deviation over pages to within 1.3 ΔE_{76} units, based on cross-validation. The organization of this article is as follows. In the next section, an experiment is designed and performed to collect tone deviation data. Then, statistical analyses are conducted to determine contributing factors in characterizing the tone deviation. Finally, regression analyses are performed to identify and validate model coefficients. Concluding remarks are provided in the final section.

EXPERIMENT

Experiments are performed on a printer of the same model as that from which the data in Fig. 1 are obtained. The tests are conducted under 15°C and 10% RH conditions. The environmental condition is chosen to represent winter printing at warehouses, repair shops, or garages, where sufficient heating is not available. The same experimental design and procedure can be applied to other environmental conditions.

The experiments focus on observing tone fluctuation immediately after starting a print job. As can be seen in Fig. 1, the initial transient tone fluctuation occurs mostly within the first 20 pages. Therefore, a print job of 21 pages is designed. A test page containing 22 patches for each primary colorant is placed every other page after the first page in the print job. The 22 patches of the same primary colorant are printed at different halftone levels, each of which corresponds to a unique amount of colorant to be deposited on the media. The rest of the pages are chosen from a variety of sample text and graphic images with coverage ranging from approximately 5% to 20%. The pages in a print job are printed continuously with constant EP parameters. Three print jobs are performed on each cartridge set. Calibration is turned off during and between print jobs. Idle periods before the three print jobs are set to 1, 2, or 3 min in a random order. Six cartridge sets with different amounts of life remaining are used. The cartridge life remaining (CLR) is denoted in percentage, where 0% represents an empty cartridge and 100% represents a new one. The highest CLR among the test cartridges is 98% and the lowest is 5%. A 90-g/m^2 white paper (HP® LaserJet HEW112400) is used as the printing media. The tone values are measured with multiple spectrophotometers (X-rite® DTP70) using D65 illuminant and 2° observer. The maximum interinstrument agreement error of the spectrophotometers is 0.5 ΔE_{94} units. Other aspects of the experiment are identical to those for the print quality experiment that produced the results shown in Fig. 1. For the three repetitions on each of the six cartridge sets, data from a total of 18 print jobs are collected during the experiment. A total of 4356 data points are collected for each primary colorant.

Data Analysis

Figure 2 displays the black tone values against job page indices for all 18 of the jobs at halftone level 96. In the plot, the same symbol represents results from the same cartridge set for different print jobs. Note that there are three jobs repeated with each cartridge. Fig. 2 shows that the tone values are at their maximum on the first page, and then decrease gradually until they reach a steady-state value. This systematic variation in tone value is observed on all six cartridge sets.

Note that Fig. 2 also shows a large tone value discrepancy among cartridges. We observe that the tone values of cartridge code B (◆) are always on the top, and those for cartridge code A (■) are always on the bottom. This is because the test pages are printed without calibration or tone correction. Most of the tone discrepancy between cartridges can be compensated by typical measurement-based calibration and tone correction.[11–13] In this work, we are focusing on observed tone variation over pages for a given print job on a single cartridge set. Typical measurement-based calibration and tone correction procedures will not eliminate this variation. It can be interpreted as the transient response of the printer to a print job.

Analysis is performed to compare tone values on different pages in the same print job. The job pages are divided into two groups. Group I includes the 1st, 3rd, and 5th pages, and group II includes the 11th, 13th, 15th, 17th, 19th, and 21st pages. Statistical paired *t*-tests[14] are conducted to determine the significances of tone value differences between pages in different groups at halftone levels 44, 96, and 126. Note that the paired *t*-test is chosen to reduce the effect of performance discrepancy among cartridges. In the paired *t*-tests, group I tone values at a given halftone level are compared to the respective group II tone values at the same halftone level. The test results indicate that group I tone values are significantly different from that of group II at a 95% confidence level (see Table I for their *p*-values). Here the 95% confidence level corresponds to a threshold of 0.05 for the *p*-values in the significance tests. The tone value differences are particularly large at halftone level 96. On average, the tone values at halftone level 96 of the 1st and 3rd pages are 4.2 and 2.4 ΔE_{76} units, respectively, larger than the mean tone value averaged over the group II pages.

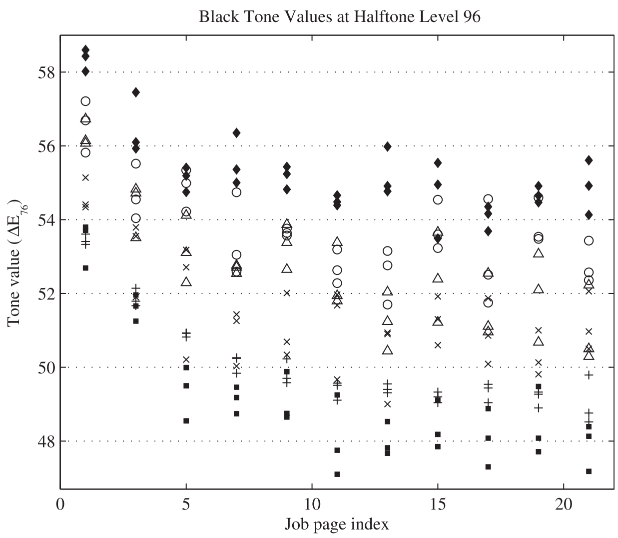


Figure 2. Black tone values at halftone level 96 under the 15°C and 10% relative humidity condition. Cartridge code legend and CLR: Cartridge A (■), CLR = 45%; Cartridge B (◆), CLR = 38%; Cartridge C (○), CLR = 73%; Cartridge D (+), CLR = 73%; Cartridge E (×), CLR = 5%; Cartridge F (Δ), CLR = 11%.

TONE DEVIATION

Tone deviation is specified to characterize the relative tone value changes over a number of printed pages for each print job. The tone deviation $d_k(x, i) \in \Re$ of the kth $\in \boldsymbol{N}$ page in the ith $\in \boldsymbol{N}$ print job at halftone level $x \in [0, 255]$ is defined as the difference between tone value $y_k(x, i) \in \Re$ of the kth page, and the steady-state tone value $y^*(x, i) \in \Re$ at halftone level x, i.e., $d_k(x, i) = y_k(x, i) - y^*(x, i)$. The steady-state tone value $y^*(x, i)$ is computed as the mean tone value of group II. The standard deviations of the group II tone values are less than 0.6 ΔE_{76} units for all of the experiment print jobs at all the halftone levels; and hence they can be used as steady-state tone values. The tone deviation is defined for each print job, respectively, so that the between-cartridge tone value variance can be eliminated. Figure 3 shows the (a) mean tone values, (b) mean tone deviations,

Table I. *p*-Values of paired *t*-tests to determine the significances of tone value differences between pages in different groups at halftone levels 44, 96, and 126 for the black colorant.

		Group II					
Halftone level 44		11th Page	13th Page	15th Page	17th Page	19th Page	21st Page
Group I	1st Page	3.4×10^{-13}	1.6×10^{-11}	1.3×10^{-10}	2.7×10^{-12}	5.1×10^{-12}	1.2×10^{-10}
	3rd Page	2.6×10^{-8}	8.8×10^{-7}	5.2×10^{-7}	6.4×10^{-9}	1.5×10^{-6}	4.1×10^{-7}
	5th Page	2.8×10^{-6}	3.9×10^{-4}	3.0×10^{-3}	5.1×10^{-6}	6.3×10^{-4}	2.6×10^{-4}
		Group II					
Halftone level 96		11th Page	13th Page	15th Page	17th Page	19th Page	21st Page
Group I	1st Page	1.7×10^{-13}	3.8×10^{-13}	6.8×10^{-12}	4.0×10^{-13}	2.5×10^{-12}	2.9×10^{-12}
	3rd Page	2.2×10^{-9}	1.1×10^{-9}	4.2×10^{-7}	2.0×10^{-9}	1.1×10^{-7}	1.7×10^{-8}
	5th Page	3.3×10^{-7}	5.6×10^{-6}	1.1×10^{-4}	1.4×10^{-7}	5.2×10^{-6}	1.9×10^{-5}
		Group II					
Halftone level 126		11th Page	13th Page	15th Page	17th Page	19th Page	21st Page
Group I	1st Page	2.5×10^{-9}	1.2×10^{-8}	4.5×10^{-8}	9.7×10^{-9}	4.1×10^{-8}	8.6×10^{-9}
	3rd Page	1.3×10^{-6}	3.4×10^{-7}	2.6×10^{-6}	2.2×10^{-7}	1.0×10^{-6}	4.2×10^{-7}
	5th Page	1.5×10^{-4}	6.2×10^{-6}	1.4×10^{-3}	6.0×10^{-5}	1.2×10^{-5}	9.0×10^{-5}

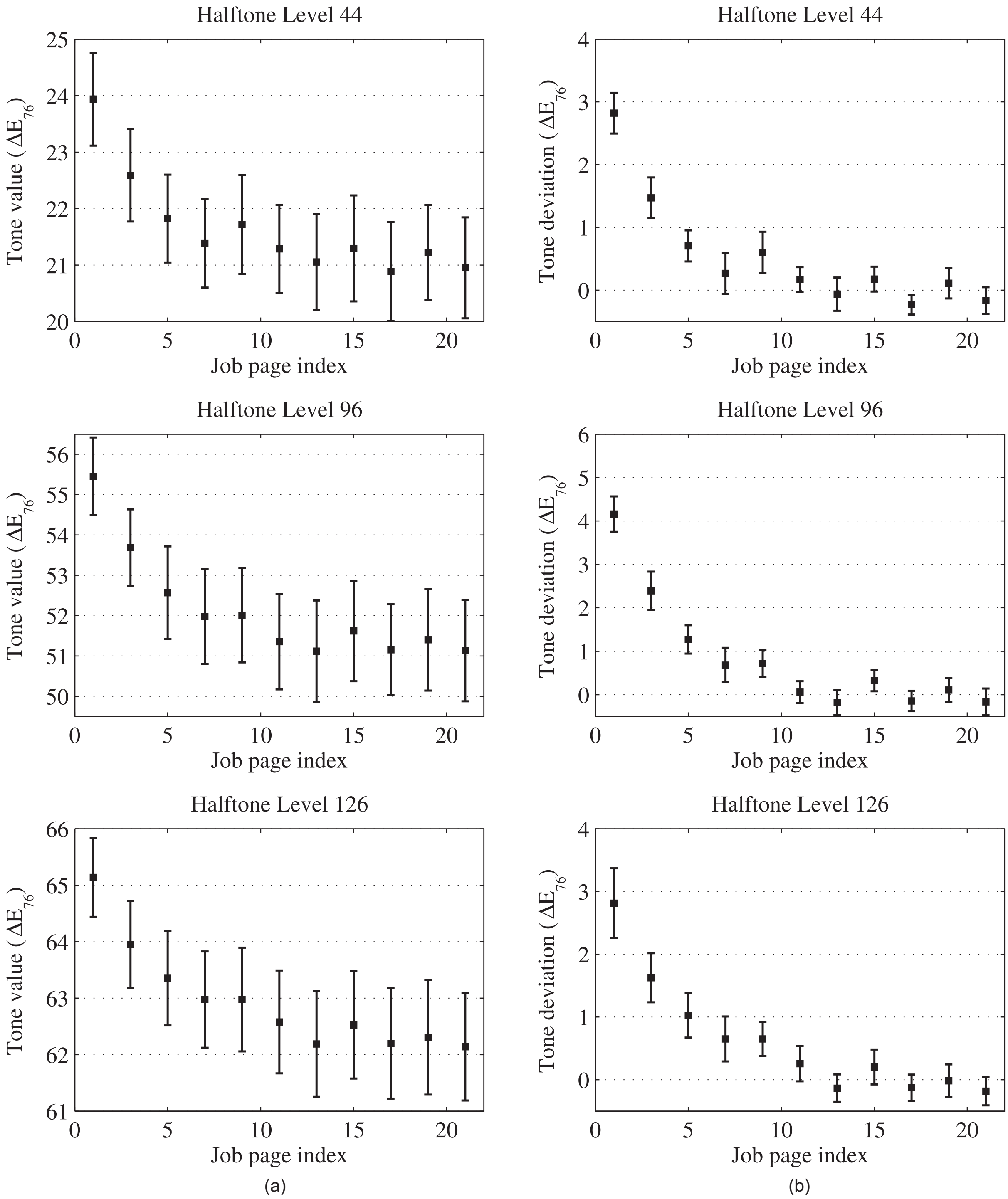


Figure 3. Black (a) mean tone values, (b) mean tone deviations, and their 95% confidence intervals at halftone levels 44, 96, and 126 under the 15°C and 10% relative humidity condition over all 18 print jobs.

and their 95% confidence intervals over all eighteen print jobs. It demonstrates that the confidence intervals of the mean tone deviations (in Fig. 3(b)) are smaller than that of the mean tone values (in Fig. 3(a)).

Length of Idle Period

Statistical analysis is performed to check if length of idle period before printing is a significant factor to mean tone deviation. The mean tone deviation $d_k(x) \in \Re$ for a given halftone level x and a job page index k is defined over all the print jobs, i.e., $d_k(x) \equiv \frac{1}{18}\sum_{i=1}^{18} d_k(x, i)$. Figure 4 displays the black mean tone deviations of the first pages $d_1(x)$ in the print jobs associated with different lengths of idle periods and their 95% confidence intervals, at halftone levels 44, 96, and 126. Analysis of variance[15] (ANOVA) is performed to determine if the length of idle period is a significant factor

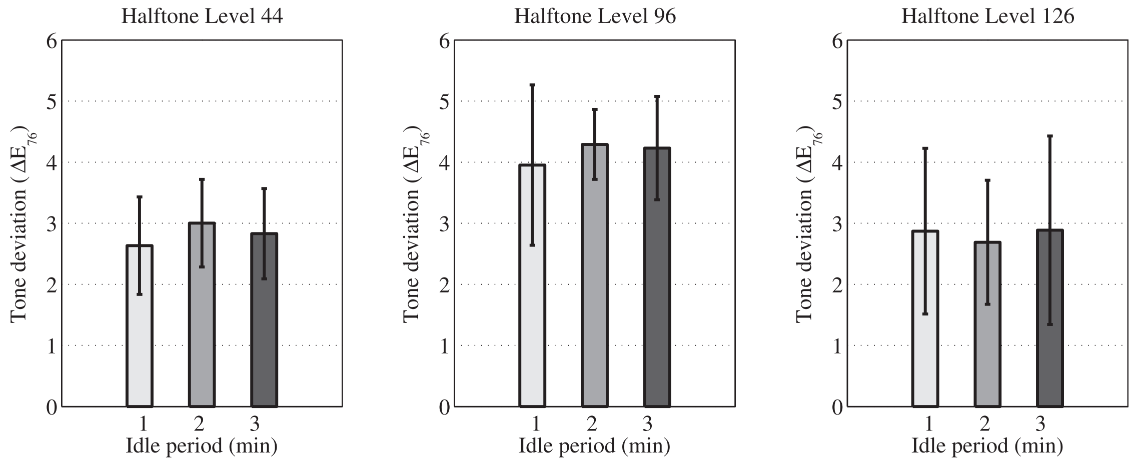


Figure 4. First-page mean tone deviations of different idle period lengths and their 95% confidence intervals at halftone levels 44, 96, 126 for the black colorant.

Table II. ANOVA table of the idle period length.

Source of variance	Sum of squares	Degree of freedom	Mean square	*F*-statistics
Halftone level 44				
Between groups	0.406	2	0.203	0.48
Within groups	6.416	15	0.428	
Total	6.822	17		
Halftone level 96				
Between groups	0.386	2	0.193	0.28
Within groups	10.466	15	0.698	
Total	10.853	17		
Halftone level 126				
Between groups	0.146	2	0.073	0.06
Within groups	19.857	15	1.324	
Total	20.003	17		

to the tone deviation (see Table II). The null hypothesis in these tests is that the mean tone deviations associated with different lengths of idle period at the same halftone levels are equal. The resulting p-values are 0.63, 0.76, and 0.95 at halftone levels 44, 96, and 126, respectively. The null hypothesis cannot be rejected at a 95% confidence level. Here the 95% confidence level corresponds to a threshold of 0.05 for the significance test. This indicates that the tone deviation is expected to consistently appear in print jobs with idle periods as short as 1 min before printing, so length of idle period should not be a model attribute.

MODELING OF TONE DEVIATION

The mean tone deviation $d_k(x)$ evolves over pages (or equivalently time) after a print job starts, and it decreases to an undetectable value within several pages. This type of tone deviation is consistently observed for idle period between 1 and 3 min under dry and cold environmental conditions. In this work, we characterize the evolution of the mean tone deviation $d_k(x)$ after the start of a print job. The resulting model can be used to identify the necessary adjustments using tone correction or other control variables to compensate the tone deviation. The performance discrepancy of steady-state tone values between cartridges can be accounted for by measurement-based calibration[11–13] and is not addressed in this research.

Model Formulation

For an in-line color EP printer, primary colors are reproduced separately. Assuming the interactions between primary colorants during transfer are minimal, the same model structure can be applied to all primary colors. The mean tone deviation from page to page is characterized by a first-order linear difference equation,[16] i.e.,

$$d_{k+1}(x) = r \cdot d_k(x), \tag{1}$$

where $r \in \Re$, $0 < r < 1$, is the decay ratio to be determined and k is the job page index. This difference equation assumes that the ratio of tone deviation between consecutive pages is constant. Note that the transient tone deviation is modeled in a discrete form, since the measurements of the tone values are made page by page. For a given initial mean tone deviation $d_1(x)$, the response of Eq. (1) can be written as

$$d_k(x) = r^{k-1} \cdot d_1(x). \tag{2}$$

Figure 5 displays the first-page mean tone deviation $d_1(x)$ across halftone levels and their 95% confidence intervals. This mean tone deviation is calculated from the data described in the Experiment section. As shown in Fig. 5, the initial mean tone deviation $d_1(x)$ depends on halftone level and is larger in the mid-tone region. As stated in Refs. 17 and 18, this may be attributed to the minimal variability

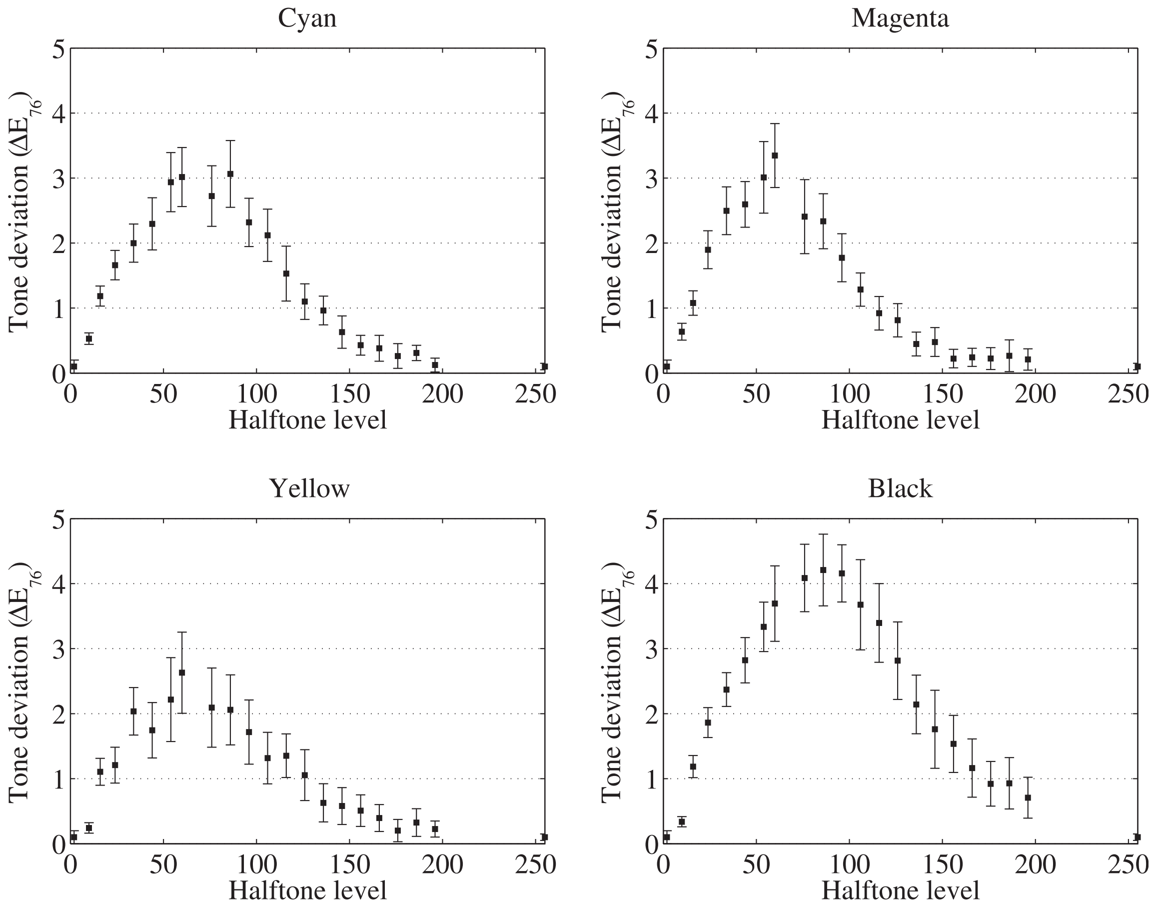


Figure 5. First-page mean tone deviations and their 95% confidence intervals under the 10°C and 15% relative humidity condition.

of uncalibrated tone values in the highlight or shadow areas due to the halftone-induced tone curve distortion and the limited available dynamic range in these portions of the tone scale. The maximum first-page mean tone deviations $d_1(x)$ across halftone levels are 3.1, 3.3, 2.6, and 4.2 ΔE_{76} units for the cyan, magenta, yellow, and black colorants, respectively. A polynomial function can be used to approximate the first-page mean tone deviation $d_1(x)$ as a function of halftone level, i.e.,

$$d_1(x) = \sum_{j=1}^{n} a_j x^j, \tag{3}$$

where $n \in \boldsymbol{N}$ is the order of the polynomial function and $a_j \in \Re$ are coefficients to be determined in subsequent regression. Note that the first-page mean tone deviation $d_1(x)$ is expected to be positive under the 10°C and 15% RH condition, and it can be negative under the 30°C and 80% RH condition (see Fig. 1).

Regression Model Development

Given the first-order difference model in Eqs. (1) and (2), and the corresponding initial response in Eq. (3), either of two system identification (ID) approaches can be used to identify the model:

Method I: Using least-squared system ID on Eq. (1) to identify the decay ratio r, and using linear regression on Eq. (3) to identify the initial mean tone deviation $d_1(x)$.

Method II: Combining Eqs. (1) through (3) and using nonlinear regression to identify all relevant parameters for the combined initial response surface,

$$d_k(x) = r^{k-1} \cdot \sum_{j=1}^{n} a_j x^j. \tag{4}$$

Fig. 5 shows that the initial mean tone deviation as a function of halftone level exhibits a third-degree behavior. A third-order polynomial function is used, $n = 3$ in Eq. (3). A total of 1188 data points are used for each primary colorant. The computation is done using MATLAB®. In method I, two linear regressions are performed separately to identify the decay ratio r in Eq. (1) and a_j, $j = 0\ldots3$, in Eq. (3), respectively. In method II, *trust region optimization*[19,20] is performed to identify the response surface model coefficients of Eq. (4) due to its nonlinear structure.

Figure 6 displays the differences between the first-page mean tone deviations predicted by the models identified using the two methods. The differences between the model-predicted tone deviations are within 0.3 ΔE_{76} units. Both

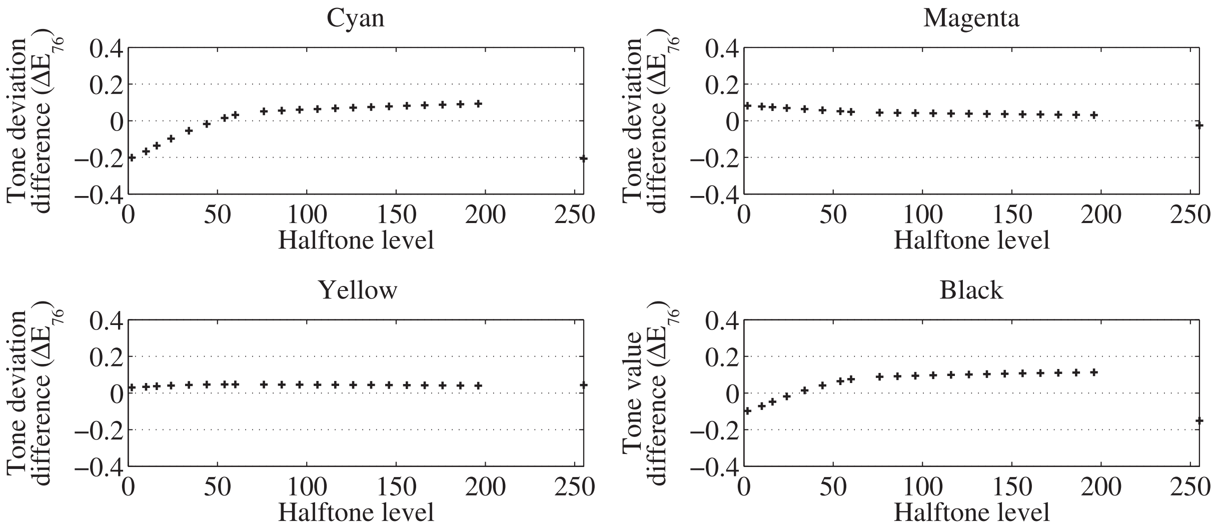


Figure 6. First-page tone deviation difference between the models identified using the two methods.

Table III. Method II decay ratios and their equivalent time constants.

	Cyan	Magenta	Yellow	Black
Decay ratio r	0.693	0.693	0.733	0.750
Equivalent time constant τ (s)	5.45	5.45	6.44	6.95

the decay ratios and the first-page tone deviation differences indicate that there exists no significant difference between the two models. Hence only the models identified by method II are examined in the following sections.

Table III lists the decay ratios r of the models identified using method II. Note that the decay ratios and their equivalent time constants indicate how fast the tone deviation approaches an undetectable value, and represent an important system characteristic. Assuming the printing speed is constant, the equivalent time constant τ can be calculated by

$$r^k = e^{-\frac{Tk}{\tau}}, \tag{5}$$

where T is the interval between printing two consecutive pages. Table III lists the equivalent time constants for method II using the nominal printing speed of 30 ppm for the test platform, e.g., $T = 2$ s. The time constants indicate that the tone values settle to within 5% of their steady-state values in 20.85 s (within 11 pages). Note that, for first-order dynamic systems, the system outputs reach 95% of their steady-state values in three time constants.

Cross-Validation

A fivefold cross-validation[21] (CV) is performed to assess the prediction accuracy of the models identified using method II. The CV is performed without replacement. Figure 7 displays the CV root-mean-squared errors (RMSE) and the mean tone deviations of the first page. The CV shows that the regression models can accurately predict the first-page mean tone deviations to within 1.3 ΔE_{76} units. The first-page and third-page CVRMSEs averaged over all the halftone levels are summarized in Table IV. It is shown that the average errors are within 0.85 ΔE_{76}. Note that the tone value measurement was made with multiple spectrophotometers, so interinstrument variance may contribute to part of the error.

The CVRMSEs are compared to the mean tone deviations (see Fig. 5) to estimate the potential reduction in tone deviation when the proposed models are applied to generate the necessary adjustment for the transient tone deviation compensation. The percentage reduction is calculated as

$$Reduction(k) = \frac{\sum_i |d_k(x_i)| - \sum_i |\hat{e}_k(x_i)|}{\sum_i |d_k(x_i)|} \times 100\%, \tag{6}$$

where $\sum_i |d_k(x_i)|$ and $\sum_i |\hat{e}_k(x_i)|$ denote the total absolute mean tone deviation and the total CVRMSE, respectively, of the kth page over all the halftone levels. The first-page and third-page percentage reductions are summarized in Table V. Note that the tone deviation percentage reduction is expected to decrease as the page index number increases. This is because the mean tone deviation $d_k(x)$ decreases exponentially for the first several pages and converges to the tone value standard deviation (see Figure 8).

DISCUSSION—DECAY RATIO AMONG COLORANTS

The regression analysis shows that the decay ratios r for the four primary colorants are within 10% of each other. Analyses are conducted to check the likelihood that the four different decay ratios $r^{(m)}$, $m = $ C, M, Y, or K, are in fact the same, and hence the transient tone fluctuation can be a system-wise phenomenon rather than a color-wise phenomenon. Bootstrapping[22–24] is applied to estimate the confidence intervals for the decay ratios. During the bootstrap analysis, the tone deviation data set is uniformly resampled with replacement for a thousand instances, mimicking

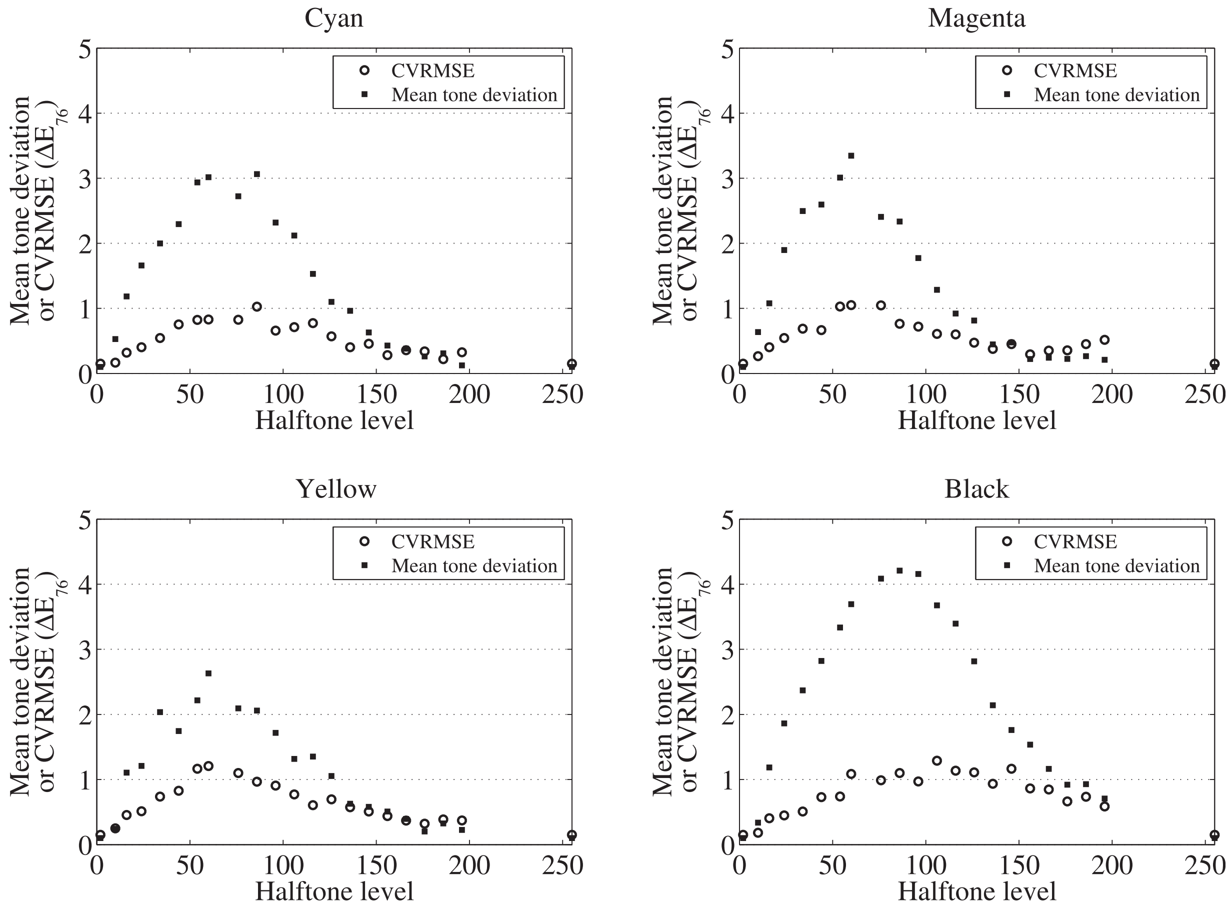


Figure 7. First-page CVRMSEs and mean tone deviations under the 10°C and 15% relative humidity condition.

Table IV. First-page and third-page cross-validation root-mean-squared errors averaged over all the halftone levels.

Page	Cyan (ΔE_{76})	Magenta (ΔE_{76})	Yellow (ΔE_{76})	Black (ΔE_{76})
1st	0.62	0.61	0.75	0.85
3rd	0.56	0.53	0.66	0.72

Table V. First-page and third-page tone deviation percentage reduction averaged over the halftone levels.

Page	Cyan (%)	Magenta (%)	Yellow (%)	Black (%)
1st	62.9	55.0	42.9	66.2
3rd	24.2	25.5	6.9	47.3

sample selection from the original population. Each resampled data set contains exactly the same number of observations as the original tone deviation data set. Then regression is performed with each resampled data set to obtain bootstrap regression coefficients. Figure 9 displays the histogram of the bootstrap decay ratios $\tilde{r}_i^{(\mathrm{C})}$, $\tilde{r}_i^{(\mathrm{M})}$, $\tilde{r}_i^{(\mathrm{Y})}$, and $\tilde{r}_i^{(\mathrm{K})}$, $i = 1,\ldots,1000$, for the cyan (C), magenta (M), yellow (Y), and black (K) colorants, respectively, and their 95% confidence limits. ANOVA is performed to determine if the mean bootstrap decay ratios for

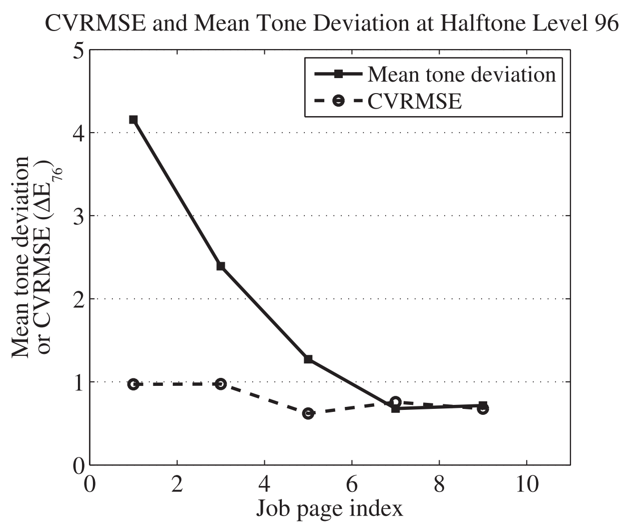


Figure 8. CVRMSE and mean tone deviation at halftone level 96 under the 10°C and 15% relative humidity condition for black colorant.

different primary colorants are equal (null hypothesis). The resulting p-value of 3.2×10^{-19} rejects the null hypothesis.

Hypothesis tests are performed to compare the decay ratio r of one primary colorant to the bootstrap decay ratios $\tilde{r}_i$, $i = 1\ldots1000$, of another primary colorant. The null hypothesis in the tests is that the decay ratios of two

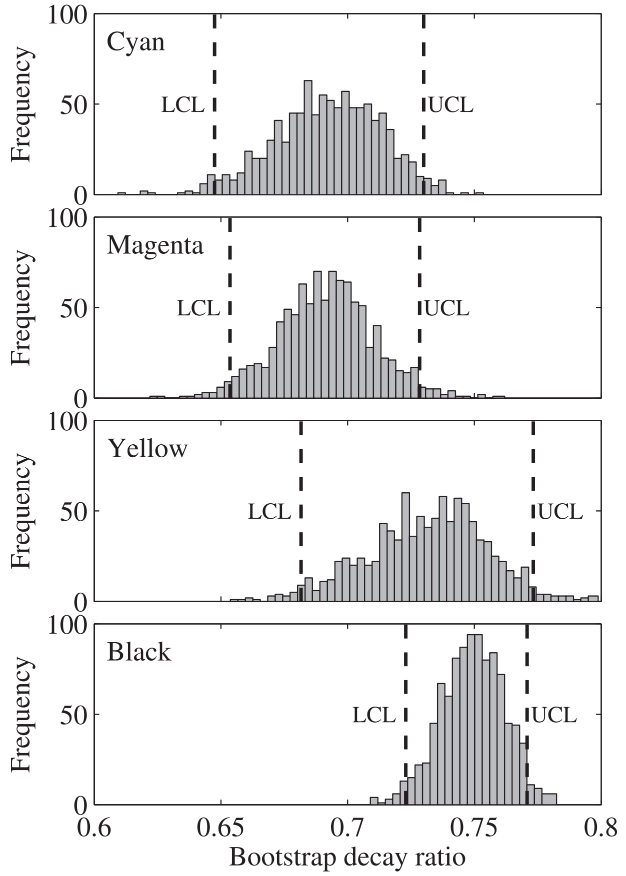


Figure 9. Histogram of bootstrap decay ratios and their 95% lower confidence limits (LCL) and upper confidence limits (UCL) for the four primary colorants.

primary colorants are equal. The two-sided, equal-tailed bootstrap p-value $p(m, n)$, where $m, n \in \{C, M, Y, K\}$, is defined as[25,26]

$$p(m,n) = 2 \cdot \min\left(\frac{1}{1000}\sum_{i=1}^{1000} I\left(\tilde{r}_i^{(m)} < r^{(n)}\right), \frac{1}{1000}\sum_{i=1}^{1000} I\left(\tilde{r}_i^{(m)} > r^{(n)}\right)\right), \quad (7)$$

where $I(\cdot)$ is a (1, 0) true or false indicator, and $r^{(n)}$ represents the decay ratio of a primary colorant n. For a confidence level α, the null hypothesis is rejected whenever the regression decay ratio r is either below the $\alpha/2$ quantile or above the $1-\alpha/2$ quantile of the bootstrap decay ratio distribution.

Table VI summarizes the resulting p-values. The null hypothesis that the decay ratios of two primary colorants are equal cannot be rejected at a 95% confidence level for some primary colorant pairs. For example, the p-values of the tests between cyan and magenta are 0.906 and 0.942, both of which exceed the threshold of 0.05 in the significance tests. This indicates that the decay ratios of these two primary colors can be considered the same. The results of significant tests for some other primary colorant pairs are

Table VI. Two-sided, equal-tailed bootstrap p-values from the pairwise decay ratio comparison tests. p-Values larger than 0.05 are underlined.

p-Value			Bootstrap decay ratio $\tilde{r}_i$ Cyan	Magenta	Yellow	Black
Regression decay ratio	Cyan	$r^{(C)} = 0.69$		0.942	0.102	~ 0
	Magenta	$r^{(M)} = 0.69$	0.906		0.102	~ 0
	Yellow	$r^{(Y)} = 0.73$	0.049	0.046		0.138
	Black	$r^{(K)} = 0.75$	0.002	0.006	0.416	

inconclusive. For example, the p-values of the tests between cyan and yellow are 0.102 and 0.049, respectively. One p-value is larger than the threshold but the other is smaller than the threshold. All in all, the tests indicate that the decay ratios can be clustered into two groups—cyan and magenta as one group, and yellow and black as the other group.

CONCLUSION

Transient tone deviation in the beginning of a print job can be observed in color EP printers under specific environmental conditions. This type of transient tone deviation is associated with time constants in seconds and cannot be compensated by typical measurement-based calibration approaches. This study characterizes this type of transient tone deviation using a first-order dynamic model. The resulting model can be used to predict tone deviation, as well as used by appropriate page-by-page tone correction algorithms. Analyses show that the tone deviation consistently appears with an idle period as short as 1 min between print jobs. It is cartridge-independent and idle-period-independent. The proposed model can accurately predict transient tone deviation to within 1.3 ΔE_{76} units based on cross-validation. The result suggests that by using the predicted tone deviation with appropriate tone correction, at least 42.9% of the first-page tone deviation can be compensated.

ACKNOWLEDGMENTS

The authors gratefully acknowledge support for this research from the Hewlett-Packard Company. They would like to especially thank Michael Lloyd and Martin Maxwell for their assistance in providing test facilities and resources. They would also like to thank Dennis Abramsohn for his valuable comments and suggestions in this research.

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