Banding Reduction in Electrophotographic Process Using Piezoelectric Actuated Laser Beam Deflection Device

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Abstract

Banding is an image artifact that appears as peroidic light and dark bands across a page. This paper presents an experimental study on the application of a piezoelectric laser beam deflection device to reduce banding in the electrophotographic process. Banding is characterized using several different measurement techniques. An empirical model of the actuator is obtained using system identification techniques by measuring the laser beam position on-line using an optical sensor. An open loop control strategy is then proposed and implemented. Experimental results showed significant improvements with the images printed using beam deflection control.

Introduction

Electrophotographic (EP) process is the underlying marking process used in laser printers. For the past 15 years, printer manufacturers have sold more than 20 million laser printers. During the EP process, a latent image is formed on an organic photoconductive (OPC) drum using a pulsed laser beam that is scanned across the OPC drum by a spinning polygon mirror. Toner particles are then electrostatically developed onto the latent image. The image is later transferred onto a sheet of paper as it comes in contact with the OPC drum. Velocity variation of the OPC drum will cause periodic perturbation in the scan line spacing, which in turn causes *banding* to occur. Banding is a type of artifact that appears as light and dark bands oriented across a printed page perpendicular to the process direction. It is also one of the most noticeable artifact for EP printers. The OPC drum velocity variation is generated by gear-to-gear interaction and vibrations caused by other engine components such as the cleaning blade.

Several researchers have studied banding artifact in the EP process. Burns et al.[1] pointed out that the laser beam positioning error would result in undesirable image noise, which degrades the image quality. Schubert[2] studied periodic image artifacts, which resulted from imperfect scanning hardware and the wobbling of the rotating polygon mirror. He also concluded that the line placement errors should be held to within 1% of the nominal value to successfully reduce banding at a particular frequency. Melnychuck and Shaw[3] identified strong correlation between the scan line spacing variation and the occurrence of banding. Loce et al.[4] modeled vibration-induced halftone banding in laser printers and pointed out that vibration within the EP print engine is mainly due to disturbances in the main drive mechanism of the EP process. Kawamoto et al.[5,6] verified that the contact charge roller and the cleaning blade both contribute to excited structural vibration and resulted in the OPC drum velocity variation. Loce et al.[7] proposed a method of using a multi-beam scanning system to compensate for banding by spacing the beams appropriately to suppress banding at certain frequencies. Later, other researchers proposed methods to reduce banding by deflecting the scanning laser beam using galvanometers or electric motors to compensate for the line spacing errors caused by the OPC drum velocity perturbation.[8,9]

In this paper, the concept of banding reduction by deflecting the laser beam using a piezoelectric actuator is investigated. A description on the different methods used to characterize banding is first given. Next, the structure of the beam deflection device is briefly explained followed by the system identification. The open loop control system is then described in detail followed by the experimental results. Conclusions are given in the last section.

Banding Characterization

The appearance of halftone banding in printouts can be quantified using several methods. Previous researchers have shown that the variation in line spacing is a major contributor to banding. The printer under study has a print resolution of 600 dpi. Assuming a constant scanning frequency and a constant OPC drum radius, variation in scan line position is mainly caused by the angular velocity variation of the OPC drum. Therefore, a reasonable method to quantify banding is by monitoring the OPC drum velocity and position using a rotary encoder mounted on the OPC axis. The estimated scan line spacing, Δy, can be derived from the encoder measurements using the relationship,

$$\Delta y = \frac{\pi n_e d}{N_e} \tag{1}$$

where n_e is the number of encoder counts, d is the diameter of the OPC drum and N_e is the encoder resolution (counts per rotation). The encoder is sampled at the process resolution, i.e. once every scan line.

Another method to measure the scan line spacing directly is by printing a special test pattern and then extract the line spacing information by scanning it at a higher resolution. A test pattern is designed by placing scan line marks at one scan line apart from each other in the process direction, see Figure 1. The location of the centroid of each mark in the process direction, $y(k)$, where k represents the scan lines, is determined by scanning the test pattern at 2000 dpi. The line spacing sequence, $\Delta y(k)$, is obtained by taking the difference of the centroids, i.e.

$$\Delta y(k) = y(k) - y(k-1) \tag{2}$$

The fill region of the test pattern is used to measure the absorptance variation of the printout along the process direction. To measure the absorptance variation, the fill area was first scanned in as a grayscale TIF image with each pixel, $I(x,y)$, where x and y denote the pixel location in the scan and process direction, respectively, taking integer values between 0 and 255. The absorptance data is obtained first by averaging $I(x,y)$ along the scan direction, i.e.

$$\bar{I}(y) = \frac{1}{n}\sum_{x=0}^{n-1} I(x,y) \tag{3}$$

and then by computing the average of two scan lines,

$$A(k) = \frac{\bar{I}(k) + \bar{I}(k-1)}{2}. \tag{4}$$

The periodic absorptance $A(k)$ fluctuates around the nominal value A_o, which can be denoted by

$$\Delta A(k) = A(k) - A_o \tag{5}$$

These fluctuations are visually perceived as banding artifacts.

The measured line spacing, $\Delta y(k)$, and absorptance variations, $\Delta A(k)$, can be transformed into its frequency spectrum using the discrete Fourier transform (DFT). The relative peaks of the frequency spectrum provide useful information about the periodic components that contribute to banding at the corresponding spatial frequencies. A comparison between the power spectrums of the derived line spacing from encoder, the scanned line spacing and absorptance is given in Figure 2. Since the appearance of banding is related to the human visual perception, the power spectrums are weighted by a normalized contrast sensitivity function (CSF) proposed by Campbell et al.[10] with a viewing distance of 18 inches. It can be seen from the plots that the derived line spacing measurements from the encoder correlated well with the scanned line spacing and the absorptance variation. All three spectral responses indicated peaks at the spatial frequencies of 8.65, 13 and 26 cycles/in.

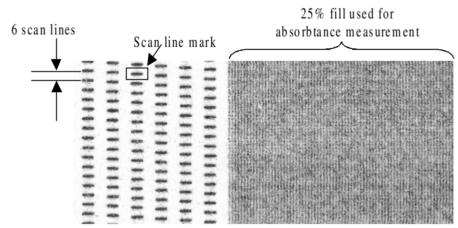

Figure 1: Magnified view of the test pattern used to measure line spacing and absorptance.

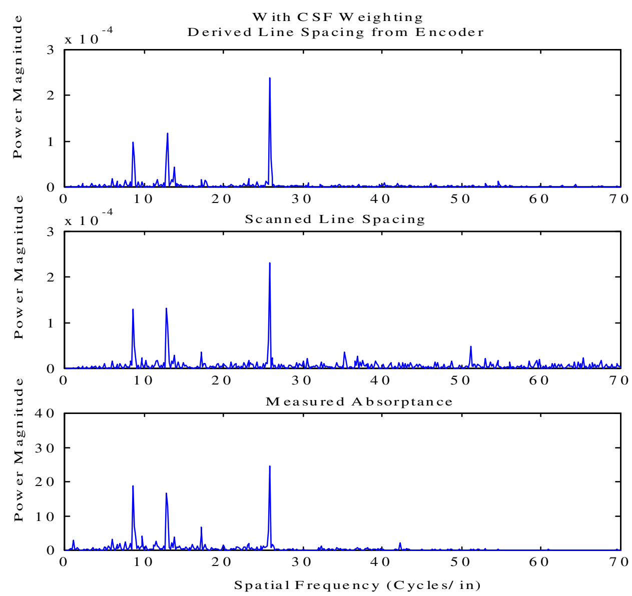

Figure 2: Comparison between the CSF weighted power spectrums of derived line spacing from the encoder, scanned line spacing and absorptance variation.

System Identification

The laser beam deflection device is a piezoelectric actuator mounted between the diode laser and the spinning polygon mirror as shown in Figure 3. The main structure of the device is a piezoelectric cantilever bimorph beam mounted at a specific angle with respect to the laser diode. The material used for the bending beam is lead zircanate titanate or more commonly referred to as PZT. A small mirror is attached to the tip of the cantilever beam to reflect the laser beam onto the polygon mirror.

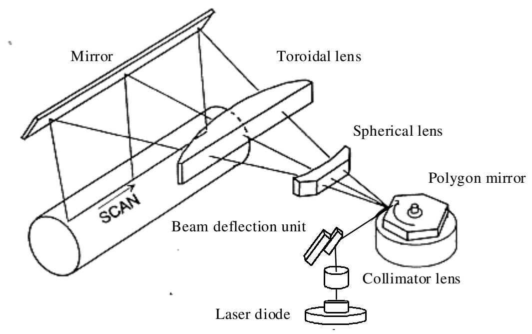

Figure 3: Location of the beam deflection device in the laser pak

The dynamics of the actuator were identified using the measurements the laser beam position using a position sensing detector (PSD). The PSD is an opto-electronic sensor capable of detecting changes in the position of an incident laser beam along a single axis using photoelectric effects. By taking measurements from the PSD installed along the path of the laser, the actuator dynamics can be identified using both frequency response and step response methods.

The frequency response of the beam deflection device was obtained using a swept-sine analysis with a dynamic signal analyzer and can be seen in Figure 4. The system input is the voltage supplied to the amplifier that drives the piezoelectric device and the output is the voltage level measured from the PSD. The magnitude plot indicated lightly damped second order dynamics at 10.8 kHz with a first order time constant at 5 kHz. Fitting the experimental result with a third order transfer function, the following empirical model for the beam deflection device from excitation voltage V_{piezo} to the output voltage of the PSD conditioning circuit V_{PSD} was obtained:

$$\frac{V_{PSD}(s)}{V_{piezo}(s)} = \frac{2.625\times10^{8}}{3.307\times10^{-5}s^{3}+1.045s^{2}+1.537\times10^{5}s+4.605\times10^{9}} \quad (6)$$

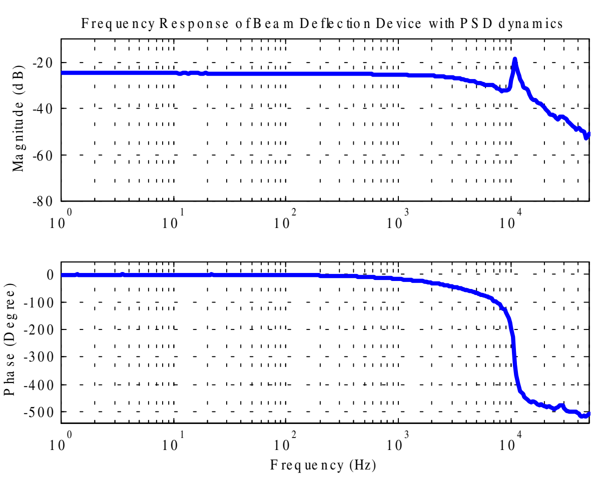

Figure 4: Frequency response of the beam deflection device and PSD circuit combined.

The step response of the system can be seen in Figure 5. The experimental measurement is compared to the simulated response using the empirical model identified from Eq. (6). Both responses agreed fairly well, except the initial transient. This is most probably due to the higher order dynamics, which are not included in the lumped third order system model. The two responses showed similar oscillatory behavior at the same frequency, 10.8 kHz. The output has yet to reach steady state before the scan line reached the end of the paper.

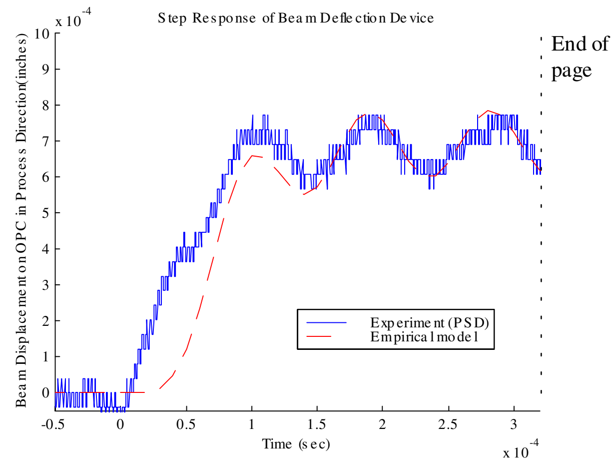

Figure 5: 30 V Step response of the beam deflection device.

Open Loop Control

The objective of open loop control is to minimize the line spacing variation at the frequency range of interest. The important frequency range include all frequencies where banding is visible, typically between 1-50 cycles/in. Since the beam deflection device demonstrated a lightly damped oscillatory response, the magnitude of the oscillations should be reduced to improve the system performance. The block diagram of the system is given in Figure 6. The measured scan line position from the encoder is compared to the desired reference value to generate an error signal. This error signal is then fed through a controller to generate the corresponding signal to control the beam deflection device. A notch filter is added to attenuate the oscillatory behavior at resonance.

The notch filter was designed to compensate for the actuator resonance at 10.8 kHz,

$$G_N(s) = \frac{s^2+3.769\times10^4 s+4.604\times10^9}{s^2+2.631\times10^5 s+4.604\times10^9}. \quad (7)$$

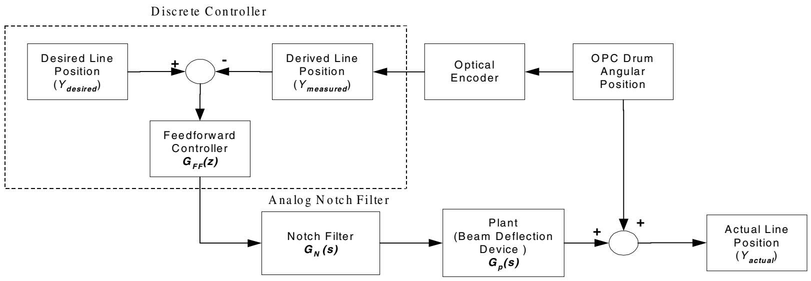

Figure 6: Block diagram of the open loop control system.

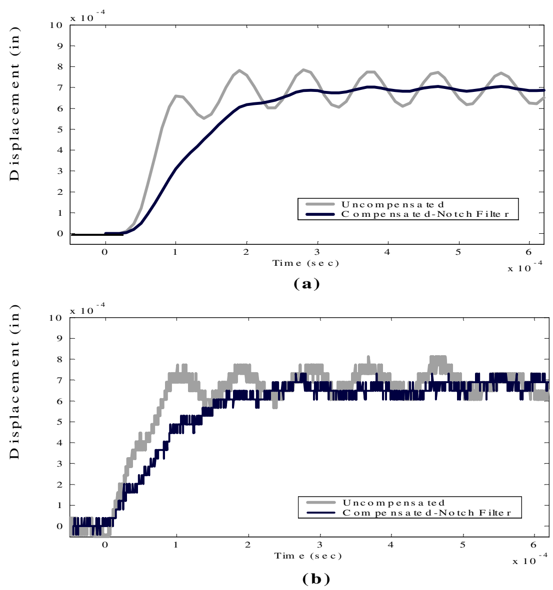

Figure 7: 30V Step response of the system with and without notch filter. Figure (a) (top) shows the simulation results and figure (b) (bottom) shows the experimental verification.

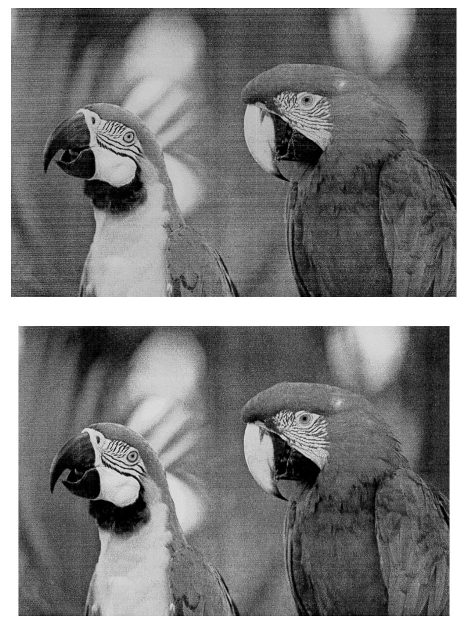

Figure 9: Image before (top) and after control (bottom).

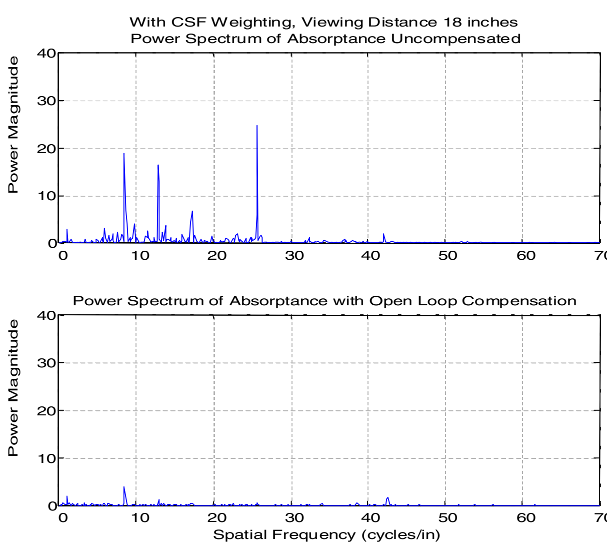

Figure 8: Power spectrum of absorptance variation before (top) and after open loop compensation (bottom).

Figure 7 shows the step response of the beam deflection device before and after compensation using the notch filter. Both theoretical simulation and experimental measurements agreed well with each other. The notch filter successfully attenuated the oscillations at the damped resonant frequency. Figure 8 shows the power spectrum of absorptance before and after compensation. It can be seen the main banding peaks are significantly reduced after beam deflection compensation. Figure 9 compares images printed with and without beam deflection compensation.

Conclusion

In this paper, an experimental study using a piezoelectric laser beam deflection device to reduce banding is presented. Methods used to characterize banding were presented. The deflection device was approximated using a third order model from the system identification results. Experimental open loop banding reduction showed significant improvements in the printed images.

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Biography

George T.-C. Chiu received his B.S. degree in Mechanical Engineering from the National Taiwan University in 1985 and his M.S. and Ph.D. degrees from the University of California at Berkeley in 1990 and 1994, respectively. Before joining the Purdue University as an assistant professor in 1996, he worked for the Hewlett-Packard Company developing inkjet printers and multi-function machines. His research interests include modeling, design and control of imaging, printing, and media transport systems, image quality and metric issues and mechatronics.