Techniques for Identifying and Analyzing Banding Sources in the Electrophotographic Process

Ulrich von Huelsen
Nexpress Solutions, LLC
Rochester, New York

Abstract

Many steps in the electrophotographic process can contribute to density oscillations in the process direction. Line spacing variation has been discussed as a contributor to density variations in great detail in the past. This paper focuses on sources other than line spacing variations and describes techniques used for identification and analysis. The sensitivity of the process to the mechanical runout of the rollers involved was investigated as well as the sensitivity to speed variations in the drive systems. Mechanical vibration or oscillation as well as electrical oscillations were studied. It could be demonstrated how beats between frequencies outside the visible spectrum can cause visible density variations. Low frequency density oscillations with cycle periods of several centimeters might not be visible to the human observer as banding but can cause process control oscillations and color inconsistency. Analysis methods for improving the frequency resolution necessary to identify these oscillations are shown together with other evaluation techniques.

Introduction

Density uniformity is one of the major challenges in electrophotographic print engines. The sensitivity of the human eye to a periodic density modulation is strongly dependent on the modulation frequency.[1,2] Even though the frequency dependence is different for reflective stimuli than for emissive stimuli, qualitatively the perceptibility functions look similar (Fig.1).

Assuming a viewing distance of 40 cm, the highest sensitivity to banding is at a spatial frequency of about 0.5 cycles per millimeter. Most banding investigations in the literature are focused on spatial frequencies higher than 0.1 cycles per millimeter.

This paper focuses on process oscillations which produce banding with a k-Vector parallel to the process direction. Rotational frequencies of process members in the electrophotographic process are often well below 0.1 cycle per millimeter. Even though the perceptibility of lower frequencies is smaller it is important to know the visual threshold for these lower frequencies.

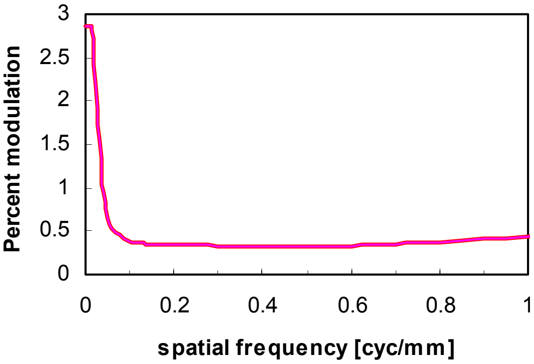

Figure 1. Perceptibility function for reflective stimuli

At very low frequencies (~0.01 cycles per millimeter) the dominant problem might be density and color consistency rather than banding perceptibility. In addition the density fluctuations can beat with the sampling frequency of closed loop process control sensors thereby creating control oscillation and further inconsistency.

Analysis Techniques

The dominant analysis technique used to investigate banding is a frequency analysis (i.e., Fourier spectrum) of sensor traces taken in the process direction. In addition to using online measurement traces as the source for the frequency analysis, the printed image can also be measured with a scanner. A representative trace is obtained by averaging the scanned densities across the image width. Interference with the halftone screen should be avoided in this step. Further information is obtained by scanning multiple images and averaging the scans in the frequency space.

Since the length of the trace that can be continuously collected might be limited to one single image the frequency resolution of the analysis might be limited as well. For a 400 mm A3 print the frequency resolution of a Fourier spectrum is 0.0025 cycles per millimeter. Often this is not sufficient. Also the noise level at low frequencies must be minimized. Detrending the raw data reduces the low frequency noise floor (Fig. 2).

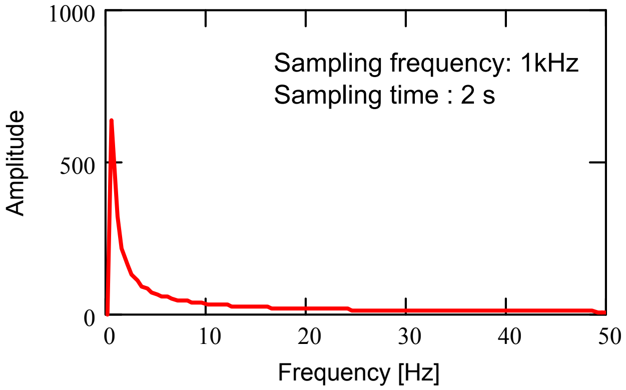

Figure 2. Low frequency region of the Fourier spectrum of a sloped line

One technique to increase the frequency resolution of the Fourier spectrum is to subtract the mean value from the raw trace and add additional zeros to the trace to create an artificially longer sampling period (Fig. 3).

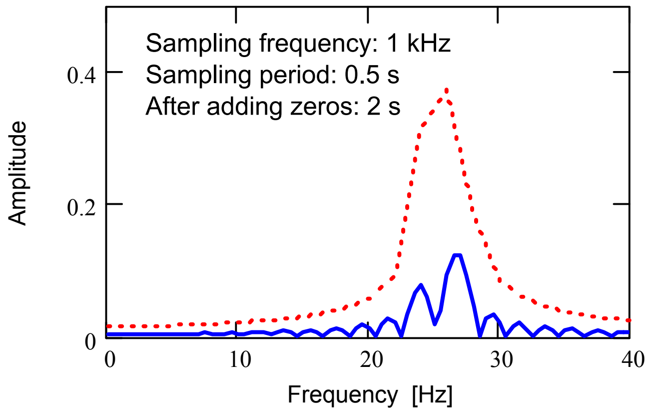

Figure 3. Fourier analysis of a synthesized signal of two sinusoidal signals at 24.5 Hz and 26.5 Hz before adding zeros (dotted line) and after adding zeros (solid line)

This technique reduces the amplitude of the signals but improves the resolution between individual frequencies by compromising the signal to noise ratio.

Another helpful technique is to use the data of multiple consecutive prints for the frequency analysis. The raw data must be collected continuously such that the data from the individual frames can be concatenated without losing the correct phase relationship of all involved oscillations. Using the Lomb normalized periodogram (Eq. 1)[3] a frequency spectrum of those unequally spaced data can be obtained.

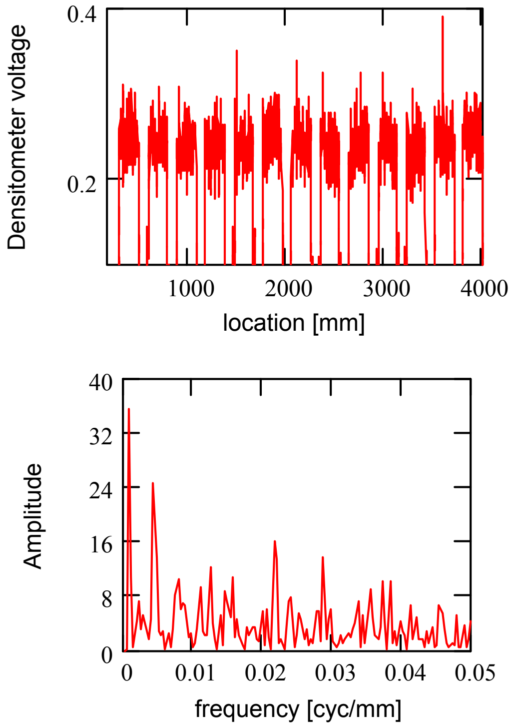

Figure 4. Banding analysis over multiple frames using a Lomb normalized periodogram

$$P(\omega) := \frac{1}{2\cdot\sigma^2}\cdot\left[\frac{\left[\sum_{k=0}^{n-1}\left(y_k - y\ avg\right)\cdot\cos\left[\omega\cdot\left(t_k-\tau\right)\right]\right]^2}{\sum_{k=0}^{n-1}\cos\left[\omega\cdot\left(t_k-\tau\right)\right]^2} + \frac{\left[\sum_{k=0}^{n-1}\left(y_k - y\ avg\right)\cdot\sin\left[\omega\cdot\left(t_k-\tau\right)\right]\right]^2}{\sum_{k=0}^{n-1}\sin\left[\omega\cdot\left(t_k-\tau\right)\right]^2}\right] \qquad \tau := \frac{1}{2\cdot\omega}\,\mathrm{atan}\left(\frac{\sum_{k=0}^{n-1}\sin\left(2\cdot\omega\cdot t_k\right)}{\sum_{k=0}^{n-1}\cos\left(2\cdot\omega\cdot t_k\right)}\right)$$

Equation 1. Lomb normalized periodogram

Percent Modulation

In order to compare the density banding spectra with the perceptibility curves the amplitudes need to be converted to percent modulation. This is only an accurate metric for sinusoidal density oscillations where the percent modulation equals the amplitude of the sine wave divided by the average of one cycle. In many cases these values underestimate the severity of the banding for multiple reasons. Fig. 5 shows a signal synthesized by adding two sinusoidal signals (a fundamental frequency and its 1st harmonic) each with average amplitude of one. The percent modulation of the resulting signal is 175% while the Fourier analysis would return a result of 100% for each of the two frequencies.

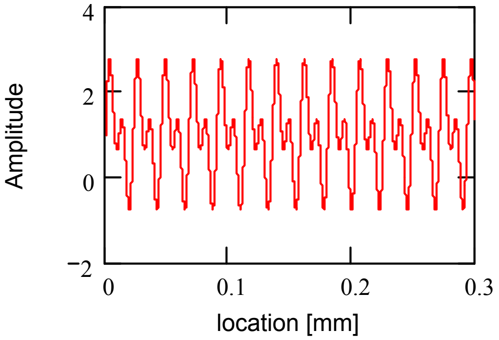

Figure 5. Synthesized signal consisting of two sinusoidal signals of a fundamental frequency and its first harmonics.

Similar underestimation of the perceptibility is true for non-sinusoidal density oscillations. Inspection of the raw data trace can be used to identify this kind of underestimation.

Origin of Banding Source

A very important step for investigating banding in an electrophotographic engine is to determine the process step by which the banding is created. Sensors are needed in between process steps that are capable of resolving the investigated oscillation. The spatial resolution of those sensors at process speed should be about a factor of 10 higher than the investigated banding frequency. With the help of online electrometers and densitometers we were able to detect whether the oscillation was present in the latent image on the photoconductor entering the development zone, whether it was present in the image charge after the development zone, and whether there was a mass lay down (or density) oscillation present before the fixing step.

The mechanisms leading to density oscillations in the charging and development steps are described below.

Voltage Oscillations in the Latent Image

Figure 6 shows a raw data trace and the frequency spectrum of the voltage on the photoconductor measured with an electrometer created by a multi-wire corona charger. An oscillation with a frequency of 4.6 Hz is observed.

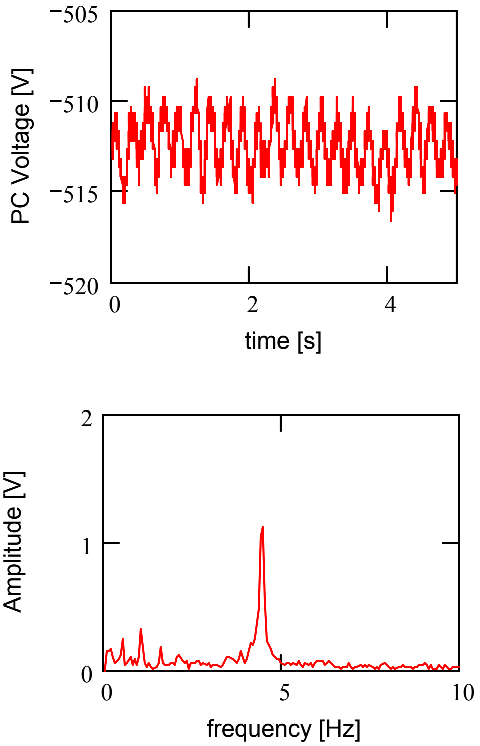

Figure 6. Raw data trace and Fourier spectrum of the photoconductor voltage

The natural frequency of the corona wires is between 250 Hz and 300 Hz. Mechanical damping of the corona wires eliminated the voltage oscillation. The low frequency voltage oscillation is created through a beat between different corona wires. Changing the tension on one of the wires slightly changes the frequency significantly. The banding was extremely sensitive to mechanical deformation of the charger body.

Banding Created in the Development Step

The development step is one of the most complex steps in electrophotography and can have several possible banding sources. Here we focus solely work was focused on the small particle development (SPD) process.[4] The development roller consists of a rotating shell with a rotating multi-pole magnetic core. Banding sources can be classified into 5 major categories:

1.) Gap Variation

The development rate in SPD development is highly dependent on the distance between the development roller and the substrate. Any cyclic change of the gap causes a density oscillation. The main contributors to those changes are the runout of the involved components, however, vibration can also be a source of gap variation.

2.) Speed Variation

The development rate is also a function of the speeds of the photoconductor, the shell of the development roller and the magnetic core of the development roller. The drivetrain of the development station has to be carefully designed to avoid any of those speed variations.

3.) Developer Mass Flow Variation

A good tool in measuring mass flow variations is the measurement of the height of the developer nap with a through-beam laser. The relation between nap height and flow is complicated and absolute calibration very difficult. Still qualitatively there is an excellent correlation between nap height oscillation and flow oscillation. In a frequency analysis, fluctuations other than those caused by the magnetic pole flips can be observed. Figure 7 shows a raw data trace and the according Fourier spectrum of a nap height measurement. A measurement of the bare roller without developer must be made in order to determine whether the measured oscillation is due to a flow variation or due to runout of the development roller. This example shows both. The peak at about 3 Hz is related to runout of the development roller while the peak at 7.5 Hz shows a flow variation.

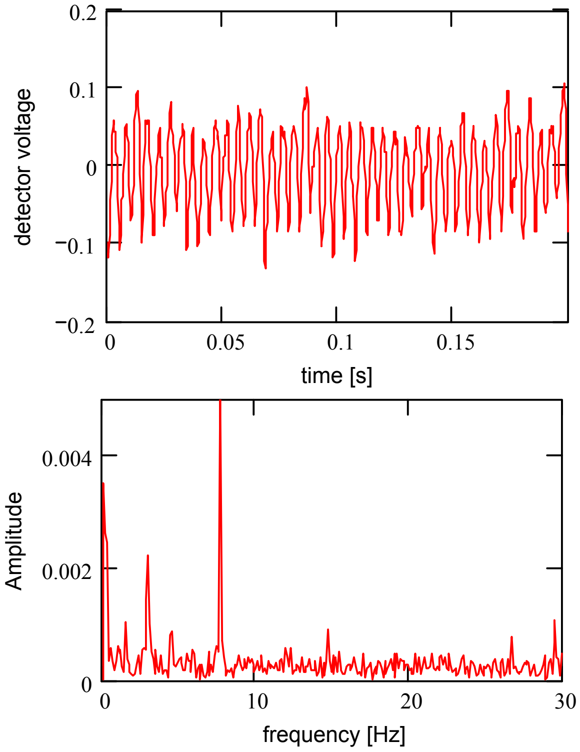

Figure 7. Raw signal and low frequency region of its Fourier spectrum from a nap height measurement

4.) Magnetic Field Variation in the Development Nip

Magnetic field oscillation in the development zone will obviously corresponds to one cycle per magnetic pole flip. This amplitude modulation of the pole flip signal can become visible as banding. A measurement of the magnetic field at the surface of the development roller can show such amplitude modulation.

5.) Electrical Oscillation

Banding can be created due to electrical oscillation of either the DC or the AC component of the development bias. This can be complicated by interactions of those oscillations with the capacitance of between the development roller and other process components.

Summary

Troubleshooting banding in images can be challenging since multiple root causes might have to be addressed for even single frequency problems. An overview has been given on measurements and analytical techniques used to identify banding sources and to determine banding frequencies. Techniques especially suitable for low frequency banding analysis have been described detail. Examples of banding sources have also been discussed.

References

1. F.L. van Nes and M. A. Bouman, "Spatial modulation transfer in the human eye", J. Opt.Soc.Am. **57**, 401-406 (1967)
2. N. Burmingham and T. Bouk, "Threshhold visibility and objectionability of banding in reflection prints", IS&T NIP 10, New Orleans, Louisiana, P548-551, 1994
3. N. R. Lomb, "Last squares frequency analysis of unequally spaced data", Astrophysics and Space Science 39, 447-462 (1976)
4. Edward T. Miskinis and Thomas A. Jadwin, "Two-component dry electrographic developer compositions containing hard magnetic carrier particles and method for using the same," US patent 4,546,060, October 8, 1985.

Biography

Ulrich von Huelsen received his PhD in Physics from the University of Goettingen in 1998. He joined Heidelberger Druckmaschinen AG in 1998 to work for the NexPress joint venture in Kiel. With NexPress he moved to Rochester, NY in 1999. Since then he has been working on Small Particle Development physics and system interactions. He is a member of the IS&T and the German Physical Society.