The Perceptibility of Random Streaking

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Abstract

A printer with good macrouniformity is capable of producing large uniform areas that would occur in business graphics. One class of macrouniformity defects arises from some aspect of marking that varies in space (such as inkjet printhead uniformity) or time (such as noise in a gear). These process deficiencies can cause visible print density variations that appear as bands or streaks. The change in print density is quantified by measuring the color variation perpendicular to the direction of the banding or streaks. The print density variations can be categorized into three classes: isolated, periodic, or random. Experimental measurements on prints show that often the Fourier spectrum of the print density is characterized by a 1/f noise spectrum. This presentation reports on a psychophysical study on the perceptibility of 1/f noise. A series of monochrome images with random streaks characterized by a 1/f noise frequency spectrum were created on a high quality printer which created very little additional noise. The samples differ by the amplitude of the noise and the average optical density of the print. The perceptibility of the streaks was evaluated by 15 observers. The perceptibility depended only on the standard deviation of L* and was independent of the average density. People are very sensitive to this type of streaks, consistent with published data for sensitivity to sinusoidal lightness variation.

Introduction

One of the image quality requirements of a high quality printer is to be able to produce uniform areas of a single color. When designing or characterizing a marking engine, the macrouniformity of solid areas must be monitored to determine if it is meeting customer expectations. A naive way to monitor macrouniformity is to measure the CIELAB color of random areas over an intended uniform color. One can quantify the nonuniformity by taking the standard deviation of the differences between the intended color and the average color. A slight variation on this technique would be to use the standard definition of image mottle.[1] In the image mottle metric definition, a region 12.7x12.7 mm is divided into 10x10 cells, and the standard deviation of the average density of each cell is the metric. However, a specification based on these types of measurement might be unnecessarily tight. These measurements do not take into account the eye's differing sensitivity to variations about different spatial frequencies.

Figure 1 – Uniform gray patches with banding. The banding amplitude is equal for all patches, but with a frequency of 0.5 cycles/mm, 0.1 cycles/mm and 0.0117 cycles/mm (1 cycle across patch).

The importance of the eye's spatial frequency sensitivity to macrouniformity is illustrated in figure 1 for periodic defects and in figure 2 for isolated streaks. Three patches with a sinusoidal banding defect are shown in figure 1. Banding of this sort is not only of theoretical interest, but can occur for print engines that have high sensitivity to a parameter that varies in time such as runout in a roll. In the figure, the banding has the same amplitude for each patch but a different frequency. The frequency of the top patch was chosen to occur near a frequency where the eye is most sensitive. The middle patch is at a frequency where the eye is less sensitive. The variation is barely visible in the bottom patch where only one cycle occurs across the patch.

Isolated streaks are another kind of print defect that can occur. The streaks can have a variety of causes – a plugged inkjet printhead, scratches on a photoreceptor, or a contaminated charging device. The perceptibility of streaks also depends on both their amplitude and spatial extent. Figure 2 shows a series of streaks with the same amplitude but again a different width. These streaks were created

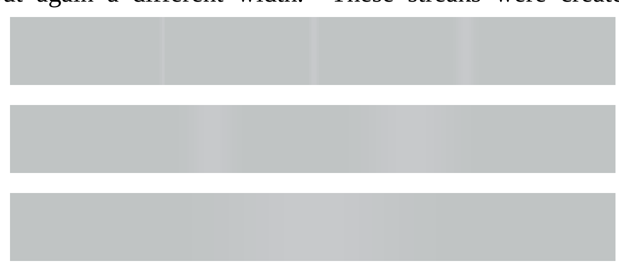

Figure 2 - 3 uniform patches with equal amplitude streaks of different widths. First row has a 0.5 mm, 1 mm, and 2 mm wide streak. Middle patch has a 5 mm and 10 mm wide streak. Bottom patch has a 20 mm wide streak.

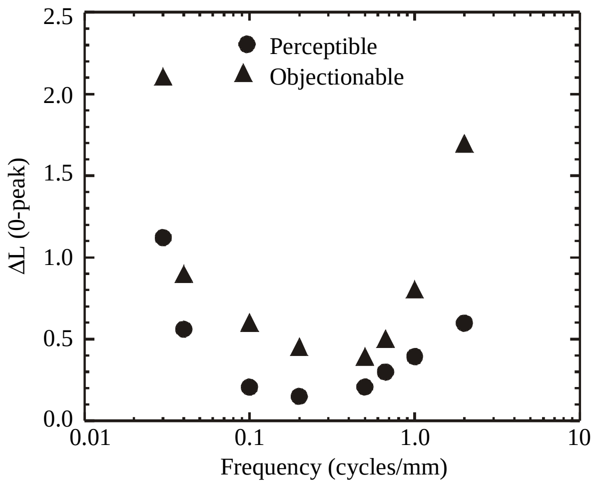

Figure 3 - Sensitivity of eye to sinusoidal luminosity variations

using a Gaussian profile, which is often seen experimentally. With this profile, streaks that are about 1 mm wide are more perceptible than much broader streaks.

Much work exists in the open literature about the human response to monochrome variations, both periodic and impulse, as a function of spatial frequency.[2-4] The perceptibility thresholds for the detection of luminosity variations are well established. In figure 3, we show the results of a psychophysical study of the perceptibility and objectionability of sinusoidal variations performed in our lab.[5,6] The squares show the amplitude (0-peak) of the L* variation (for black halftones) below which banding is not perceptible. The diamonds give the threshold where the average observer would note the variation as objectionable. The results are expressed in terms of cycles/mm on paper at normal reading distance (~40 cm).

1/f noise in prints

Periodic variations and isolated streaks are not the only kind of one-dimensional noise that can occur in prints. A random streaking is observed in solid areas of selected electrophotographic printers currently in the market. To demonstrate the existence of this noise, we scanned full-page halftone prints generated at a 25% area coverage on HP 8500, Lexmark 1200, and Okidata 8C electrophotographic printers. We quantified the streaking by scanning the prints on a professional flatbed scanner. We extracted a portion of the image using a narrow rectangular window, averaged the scanner response along the width of the window, and converted the scanner output to L*. Figure 4 shows a plot of luminosity vs. position for the three printers.

The variation of luminosity in these plots is dominated neither by isolated spikes nor by periodic bands. Instead the profile has a more random behavior. The luminosity variation seen in the prints arises most likely from a combination of noise contributors from the different subsystems in the printer. In nature, a variety of complex dynamical systems give rise to a noise spectrum that is

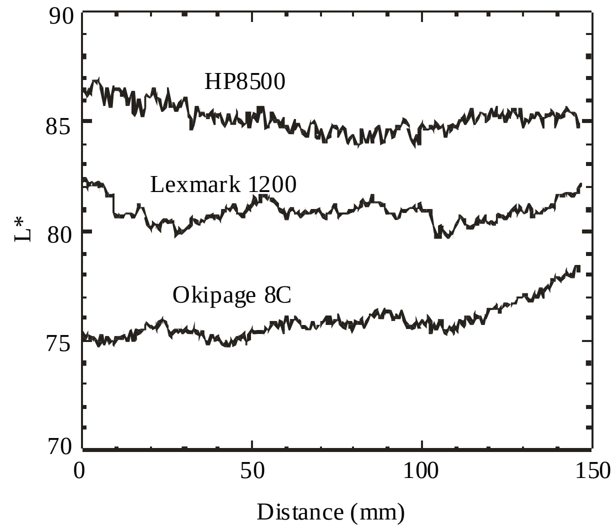

Figure 4 - Scan of L along the short direction for 3 electrophotographic prints of "uniform" low density gray halftones*

described as 1/f, that is the Fourier spectrum of the response of the system varies as the inverse of the frequency.[7]

This spectrum is seen in the Fourier transform of the scans of the prints. In figure 5 the amplitude of the noise is plotted as a function of frequency on a log-log scale for the Lexmark print. The trend in the dependence on frequency in this plot is roughly linear, implying that the amplitude of the noise is inversely proportional to the frequency

Therefore, if a printer is being designed that is dominated by 1/f noise, then it is the perceptibility of this noise that must be determined. It is not immediately straightforward to predict how perceptible 1/f noise will be. Will the random excursions of the intensity be as perceptible as if they were individual streaks? Can the perceptibility of the random streaking be related back to a superposition of the perceptibility of the individual frequencies? In this paper, we generated artificially a series of images showing 1/f noise of different amplitudes, and then performed a psychophysical study to determine the perceptibility of this noise.

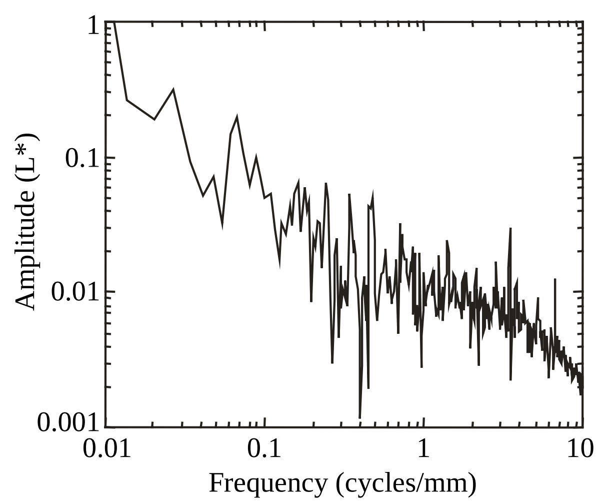

Figure 5 - Fourier transform of the Lexmark 1200 scan

Generation of Noise Samples

A profile of L* vs. position was artificially created by generating 1/f noise in Fourier space and taking the inverse Fourier transform to get a real space signal. Specifically, a random spectrum is generated according to

$$A_i = \frac{A_0}{f^{\alpha}_{\max(i,i_0)}}\left[1 + N\left(0, \frac{A_0}{f^{\alpha}_{\max(i,i_0)}}\right)\middle/2\right]$$

$$\phi_i = U(0,2\pi)$$

Here i is the frequency index, i_0 is a low frequency cutoff to the 1/f noise spectrum, A_0 is a scaling factor of the amplitude of the distribution, $N(\mu,\sigma)$ is the normal probability distribution function with mean μ and standard deviation σ, and $U(x_1,x_2)$ is the uniform probability distribution function giving random numbers distributed uniformly between x_1 and x_2. This form for the artificial distribution was chosen to give a spectrum that qualitatively resembles the Fourier transforms of experimental data.

The normally distributed random numbers cause the fluctuations about the 1/f trend. To generate test prints, 2000 complex conjugate pairs were calculated in the Fourier transform, resulting in 4000 points when the inverse Fourier transform was calculated. We chose the calculated points to represent gray levels at 1/600 inch intervals, so the data corresponds to a region 6-2/3” long. The cutoff frequency i_0 was necessary to prevent large low frequency excursions in the data that were not present experimentally. i_0=10 was chosen in the calculations, corresponding to 0.06 cycles/mm (~17 mm period).

Each of the sets of points was scaled by one of 10 scaling factors. The scaling factors were roughly distributed over a factor of 8 to cause the printed image to span the range between objectionable and imperceptible banding. The samples were made with one of five average area coverages (15%, 25%, 40%, 60%, and 80%) giving a total of 50 unique profiles.

Because each sample was generated from a different 1/f-noise profile, the streak pattern differed from sample to sample so an observer would not concentrate on a particular feature or area of the samples. To get a sense of the variation in the prints, 4 of the 50 prints are reproduced in figure 6. The dimensions of the images produced here are .375” by 3.375” segment of the test samples but are to scale. The actual amplitudes will depend on the specific monitor or printer used to display the images; they are intended to be illustrative only. The figure shows 2 prints of differing 1/f noise amplitudes at 2 different print densities.

Figure 6 - Sections of the 1/f noise images from top to bottom: maximum amplitude at 25% *area coverage, 1/2 maximum amplitude, maximum amplitude at 40% area coverage, 1/2 maximum amplitude*

Test samples were printed using a well controlled printer which added very little uncontrolled noise. They were then affixed to stiff, opaque white cards. Different gray levels were achieved by using a halftone of a similar frequency to that for the electrophotographic printers. From the sensitivity to periodic variations, we knew that changes less than 0.1% could be perceptible, while at 256 gray levels only steps of 0.4% can be achieved. It was therefore necessary to use a variant of noise encoding[8] to print patterns corresponding to non-integer graylevels, since clipping the disturbance to only integer values could have changed the nature of the frequency spectrum. The local gray level printed could be adjusted to match any gray level from a continuous distribution.

Test Procedure

The 50 samples were put in random order and shown to each of 15 observers. Observers viewed the samples under normal office conditions and at normal reading distance, which typically varies over a range of ~10-15%. Given the multitude of spatial frequencies which are present in each print sample, this amount of variation does not cause a significant shift in the perceptibility of the samples. At worst, it softens the thresholds. Moreover, real prints are viewed under a range of conditions.

The subjects sorted the samples into one of 3 piles: (1) No visible variation, (2) variation visible but not objectionable, and (3) variation is objectionable. The rating for each sample was then recorded.

Results and Analysis

The amount of noise in each image was quantified by the standard deviation of the set of L* values which make up the cross section of the noisy image (σ_{L*}). This may not be the most appropriate metric. It doesn’t take into account the eye’s sensitivity difference to the different spatial frequencies. Since all samples used for this study have the same spectrum of spatial frequencies, σ_{L*} captures the magnitude of the variation nicely. As will be seen, it can be used to predict the average observer’s response to the 1/f noise samples. Because of the low frequency cutoff in the samples, there is no skew in the data which might be imperceptible yet give a σ_{L*} that would not be related to the higher frequency visible fluctuations.

Different people respond differently to the same image, so there is a spread in people’s responses to the 50 images. For each image metrics were extracted: the fraction of the respondents rating the noise perceptible, and the fraction of the respondents rating the noise objectionable. For the 25% area coverage image, both fractions are plotted vs. σ_{L*} in figure 7. The curves are fit with the functional form

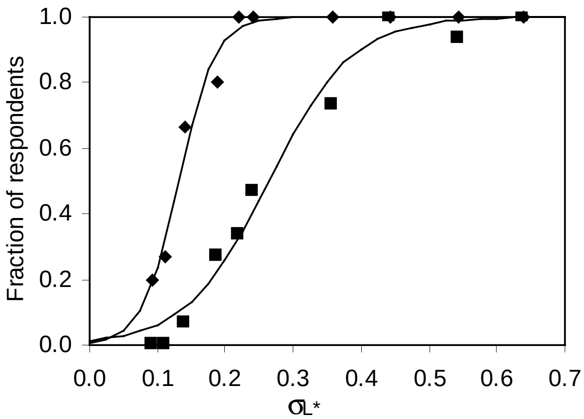

Figure 7 - Fraction of respondents ruling sample perceptible (diamonds) or objectionable (squares) as a function of the standard deviation of L for average area coverage of 25%.*

$$R = \frac{1}{2}\left[1+\tanh\left(\frac{\sigma_L - \sigma_{L0}}{w}\right)\right] \quad (2)$$

This functional form captures the spread in the responses through w and the point where 50% of the observers rate the sample as failing their criterion through σ_{L0}

Figure 8 shows the points where 50% of the observers rate the noise as perceptible (diamonds) or objectionable (squares) for each of the 5 area coverages. Although there is some noise in the data, within the accuracy of the experiment, the thresholds are independent of L*. The original CIELAB definition of L* from the XYZ tristimulus values was made to force perceived luminosity differences to be independent of the optical density. This independence still holds when the differences manifest themselves as random noise.

Discussion

The 1/f noise study shows that quite small variations in luminosity can be detected. This is consistent with the measurements for the periodic variations. At the spatial frequency to which the eye is most sensitive, a zero-peak amplitude of 0.15 ΔL can be detected. This corresponds to a standard deviation in the L* values of 0.11, which is about equal to the perceptibility limit indicated in figure 8.

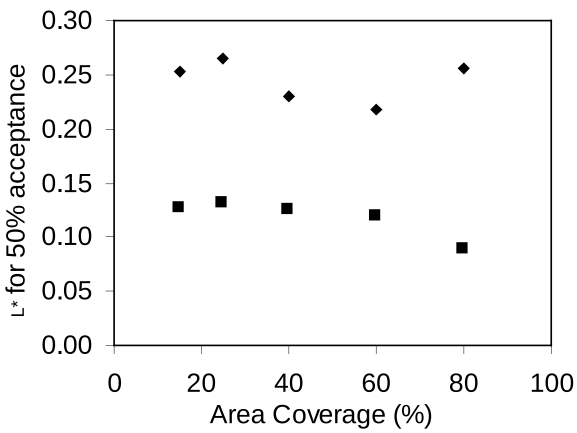

Figure 8 - Standard deviation of L that causes 50% of observers to judge the image as objectionable (diamonds) or perceptible (squares)*

If the eye is responding to the Fourier transform of the noise, then it should be possible to make a generalization about the detectability of noise with a different spectrum. If the Fourier spectrum of the noise is overlaid against the perceptibility curve of figure 4, then any portion of the spectrum that is above the perceptibility limit should be detectable. One has to be careful in making this comparison. The perceptibility to sinusoidal variations is expressed as an amplitude of a single frequency. The frequency spectrum of the noise is spread out over all frequencies, and the amplitudes depend how many points are sampled from the scan of the real space profile. These two spectrums can be compared directly if one multiplies the noisy spectrum by the square root of the number of points in the Fourier spectrum (the square root arises from how different Fourier terms with random phases combine). Figure 9 shows the Fourier spectrum of the noise at the perceptibility limit along with the perceptibility limit for sinusoidal variation of figure 4. The spectrum in figure 9 was generating so that when transformed it would gives the 1/f perceptibility limit of σ_{L*}=0.13. The figure shows that it is the low frequency terms that exceed the threshold. The spectrum is a factor of two higher than the perceptibility of sinusoidal variations. This may be due to the fact that the presence of higher frequency noise makes the lower frequency noise less perceptible.

Conclusions

We have shown that the random streaks that printers can give in uniform solid areas can be characterized by a 1/f noise spectrum. A careful psychophysical study gave the perceptibility limits of artificial 1/f noise samples. The standard deviation of L* variations gave an adequate metric to determine the perceptibility of this type of noise. The perceptibility was found to be independent of average

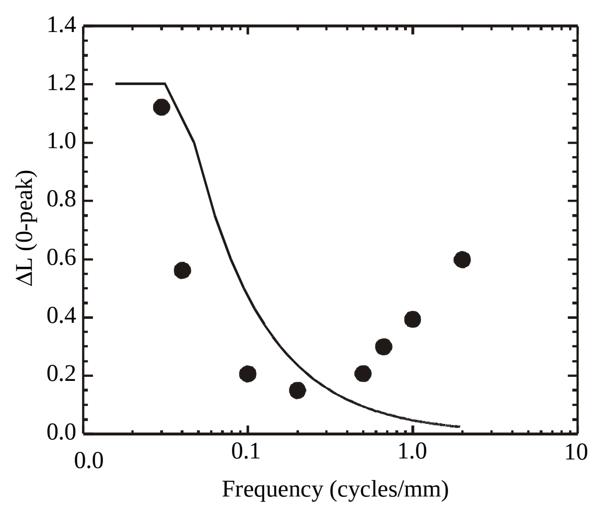

Figure 9 - Noise spectrum at the perceptibility limit (with randomness removed) plotted against the perceptibility limit for sinusoidal oscillations.

optical density when the σ_{L*} metric was used. The high sensitivity to 1/f noise is comparable to that seen for sinusoidal variations.

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Biography

Howard Mizes received his B.S. degree in Physics from the University of California at Los Angeles in 1983 and a Ph.D. in Applied Physics from Stanford University in 1988. Since 1988 he has worked in the Wilson Center for Research and Technology at Xerox Corporation in Webster, NY. His work has primarily focused on the development process, including toner adhesion, toner transport and image quality issues. He is a member of the IS&T and the American Physical Society.