Color Noise Analysis

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Abstract

Graininess is one of the important image quality metrics in the photographic quality. In this paper, we will report an investigation of our evaluation model for color graininess. In this evaluation model, overall image noise is predicted as a graininess index (GI) to the average lightness for each patch image, and the GI is calculated from two image noise metrics, the lightness noise (LN) and the chromatic noise (CN). These are estimated respectively from fluctuation of the brightness component and of the chromatic component in the image.

Concerning this evaluation model, we made a subjective evaluation experiment in order to find the optimum weighting factor for CN. The correlation coefficient between the subjective evaluated levels and the optimized GI improved greatly compared with the case where CN is not considered, or the weighting factor for CN is zero. Using this optimized GI, we evaluated the color graininess for several hardcopy images with different printing types, like silver halide, electrophotography, ink jet, and so on, and we studied the perception of noise on color images.

Introduction

Color printers have come to be widely used at office and home, and the image quality level is also demanded higher every year. Especially, there are a lot of chances for color printers to output pictorial images, and many users expect a smooth (nearly graininess free) image like the silver halide. Therefore, it is interesting to know the difference in each image quality between the silver halide and the other printing types, including ink jet of which image quality level has been remarkably improved lately, thermal, electrophotography, and so on. In this paper, the term "graininess index" is used to describe the perceived noise on color images, and its metric becomes an index for the comparison stated above.

For black and white images, the following conventional metric [1] has been widely used to evaluate the graininess. It is based on the integration of the Wiener Spectrum (WS) for reflection density, which is moreover multiplied by the transfer function of a human vision, and the integrated value is furthermore multiplied by the visual sensitivity function, exp(-1.8d), for the average reflection density d of the patch image. Similar to this conventional metric, we have proposed a new metric of the lightness noise [2], which is also based on the integration of the WS for lightness instead of reflection density, and we have adopted a new visual sensitivity function to the average lightness of the patch.

On the other hand, although a small number of metrics for chromatic noise have been proposed [3, 4], they have not widely accepted because of doubt in signification of chromatic component for the perception of noise. For instance, in the metric to evaluate the chromatic noise from the data of chromaticity a* and b* in the image, it was concluded that the lightness noise was dominant for the perceived noise on color images [4]. However, we consider that the noise by the fluctuation of chromatic component also has the possibility to become a factor for debasing the perceived noise on color images. We have proposed a new metric of chromatic noise for color images by using the data of metric chroma and hue-angle, which correspond to the chromatic information recognized finally in the human visual system [5]. In our metric, the chromatic noise is estimated by supposing their distributions of chromatic components on a*b*-plane, of which metric chroma and

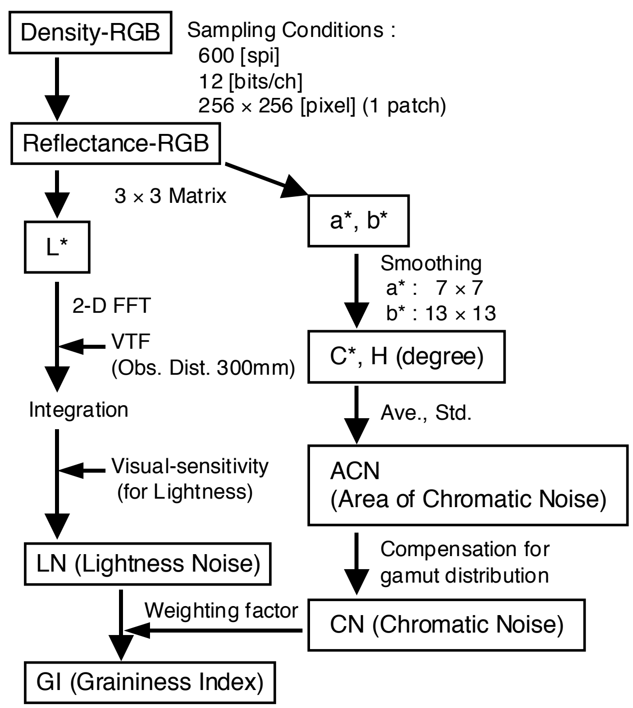

Figure 1. The flowchart to evaluate the color noise as graininess index (GI). The GI is estimated from both the Lightness Noise (LN) and the Chromatic Noise (CN).

hue-angle are calculated from the data of chromaticity a* and b*, after having processed for their spatial frequency responses of vision.

In order to verify our consideration and to optimize the weight for the chromatic noise to the lightness noise, we made a subjective evaluation experiment for the graininess index, which is estimated from the above-mentioned metrics, or the lightness noise and the chromatic noise. Further, we investigated the signification of chromatic noise for the perceived noise on color images.

Objective Evaluation

Figure 1 shows the flowchart of our objective evaluation model to estimate the color noise as a graininess index. The image data is sampled with a drum-scanning type microdensitometer by 12 bit/ch depth. A high signal-to-noise ratio is obtained compared with an input device such as a CCD, because each channel is read with one photomultiplier. The output data with reflection density RGB are converted into reflectance RGB in order to improve the accuracy of approximation on the next step. The reflectance RGB is then approximated to the XYZ by using a 3 × 3 matrix calibrated beforehand with the standard color target based on ISO12641. Finally, the XYZ is converted into the L*a*b* in CIE 1976 color space.

Lightness Noise

As expressed with equation (1), the physical value g for each patch image is evaluated from the integration of WS for lightness, which is multiplied by the visual transfer function, VTF at viewing distance 300 mm. Then, the lightness noise, LN, is defined with equation (2), where the physical value g is multiplied by the visual sensitivity representation, f (L), for the average lightness of each patch.

$$g = \Sigma\,\Sigma\,\{\, WS\,(u_{x,y})^{1/2} \times VTF\,(u_{x,y})\,\} \quad (1)$$

$$LN = f\,(L) \times g \quad (2)$$

where $u_{x,\,y}$ is the spatial frequency in cycle/degree, and f (L) is a pair of linear functions intersecting respectively on the average lightness of about 69 as shown in Figure 2.

In Figure 2, the thick lines denoted as JND (Just Noticeable Difference) line consist of two linear equations derived from threshold patch images which are beginning to feel graininess at a viewing distance of 300mm. With an observational test, we selected the threshold patch images in test chart of gray scales, made by accurate monochrome halftone tints ranging from 65 to 200 lines/inch, and 5 to 95% area coverage. Lbd is the x coordinate of the intersection of JND lines, and all points on JND lines are supposed to be a limit level which hardly feel graininess for each lightness. Therefore, we can define the physical value g at x=Lbd as the lightness noise, LN, and achieved a visual sensitivity representation to the average lightness on JND lines. In addition, we conceived a lightness dependence model for the other area as shown with two pairs of lines in Figure 2, for example. Each line shares the x-intersections of L1 or L2 (L1 < L2) with JND lines. We assumed that all points on each pair of lines intersecting on Lbd (x = 69), are

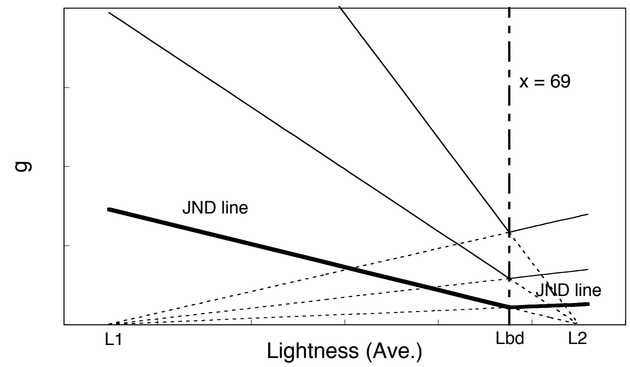

Figure 2. Lightness dependence model assumed from two JND lines. Each pair of lines intersecting on Lbd (x = 69) is extended to intercept the x-axis at L1 or L2, respectively.

perceived as equal noise independent of lightness as well as the case of JND lines. This lightness dependence model of visual sensitivity representation is expressed with equation (3) or equation (4). Further details are described in the proceedings of IS&T's NIP12 [2] and NIP13 [5].

$$f\,(L) = (\,Lbd - L1\,)\,/\,(\,L - L1\,) \quad (\,L \geq Lbd\,) \quad (3)$$

$$f\,(L) = (\,Lbd - L2\,)\,/\,(\,L - L2\,) \quad (\,L < Lbd\,) \quad (4)$$

Chromatic Noise

The chromatic noise is evaluated by using a similar concept of RMS (root-mean-square) granularity, which has been widely accepted in the field of silver halide. Three kinds of components; brightness, saturation, and hue are regarded as the information recognized finally in the human visual system. Therefore, we consider that it would be reasonable to evaluate the chromatic noise with the corresponding metric chroma and metric hue-angle.

First, the chromatic spatial frequency responses are considered to be a type of low-pass filter. For the image plane of a* and b*, with the case where the resolution is 600 spi (samples/inch), we adopted smoothing filters of which sizes are 7 × 7 pixels for a* and 13 × 13 pixels for b*, respectively. Each filter size is selected to match with human visual responses, and their spatial frequency characteristics are described as sinc functions. That is to say, for each spatial frequency response, the chromaticity data of a* and b* are processed on the real space, while the lightness L* is processed on the frequency space.

Secondly, metric chroma and hue-angle for each pixel, are calculated from the processed chromaticity data of a* and b*, and then we computed the average and the standard deviation of them for each patch. Figure 3 shows an illustration for the notion of ACN (Area of Chromatic Noise). It can be guessed that the fluctuation of chromatic components, metric chroma and hue-angle, would be within plus and minus three times of each standard deviation from the coordinates of their average. That is, it is possible to regard the ACN as the chromatic distribution on a*b*-plane, and is calculated by subtracting the small sector from the big one as shown in Figure 3.

In addition, ACN is processed for the average lightness as expressed by equation (5) in consideration of the actual gamut distribution, and the processed value is defined as the chromatic noise, or CN.

$$CN = ACN / \{ L \times (100 - L) \} \quad (5)$$

Note: The equation (5) is improved on the equation in the proceeding of NIP13 [5] in order to reduce the influence of CN to GI in the low lightness range.

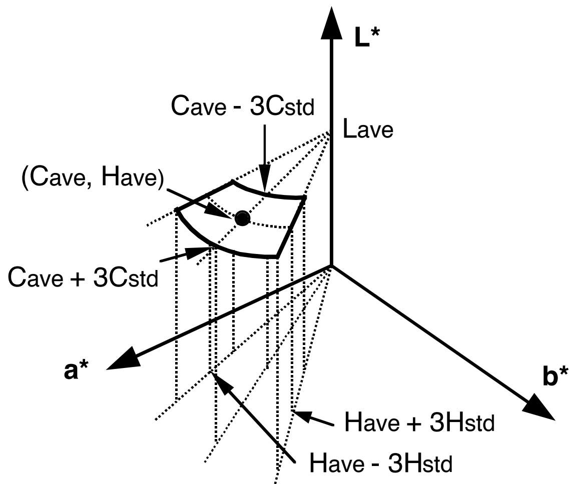

Figure 3. Notion for the area of chromatic noise (ACN). Lave, Cave, and Have are defined as the average of the Lightness, Chroma, and Hue-angle for each patch image. Cstd and Hstd are defined as the standard deviation of Chroma and Hue-angle for each patch.

Graininess Index

Graininess index, GI, is represented by the square root of the sum of squares for the lightness noise LN and the chromatic noise CN as expressed by equation (6), where k is a weighting factor. LN and CN are numerical values, and they have different physical meanings respectively. In the proceeding of NIP13 [5], we evaluated GI for the case where k=1, or we thought that the weight for these two noise metrics might be roughly equivalent. In this report, we attempted the optimization for the weighting factor k with a subjective evaluation experiment, which will be explained in the next paragraph.

$$GI = (LN^2 + \mathrm{k} \times CN^2)^{1/2} \quad (6)$$

Subjective Evaluation

Paired Comparisons

In order to find the optimum value for the weighting factor k, we tried a subjective evaluation experiment for 51 samples, which were made with an electrophotography and were selected in consideration of the brightness and the roughly perceived noise. In this experiment, we adopted a method of paired comparisons by Scheffé [6], which was obtained the relative level of all samples by relative judgments. Because we considered that it would be more difficult to judge absolutely for color images than black and white ones. These paired comparisons can make up a psychological scale for all samples by comparing relativity all possible pairs including an opposite combination, like A over B, and B over A, for instance. In general, it is supposed that more detailed judgments would be enabled than absolute judgments in which one sample is shown and judged.

Five observers who have been engaged in image quality, assessed 51 samples by 2550 (= 51 × 50) kinds of relative comparisons respectively under the illuminated conditions of a general office environment (about 500 *lx*). The judges' preferences are expressed on a 3-point scale, -1 (better), 0 (almost same), and +1 (worse). (Because the value of GI becomes larger as the perceived noise increases.) The experimental results were described as the mean preference for each sample, and the average value of five observers assumed to be the subjective evaluated levels. For each sample, the mean preference expresses how good or bad it was judged, and corresponds to the normalized winning percentage for all samples between -1 and +1 to put it simply.

Figure 4 shows the relationship between GI and the subjective evaluated levels. From equation (6), if k = 0, then GI is just equal to LN. The correlation coefficient γ was 0.72 in the case where the influences of chromatic fluctuation were not considered. We analyzed the relationship between the weighting factor k and the correlation coefficient, and found the optimum value of k = 2.76, where the highest correlation coefficient γ = 0.91 was obtained. The correlation between GI and the subjective evaluated levels improved greatly, and the effectiveness for CN to LN was confirmed. Therefore, the optimized GI is expressed by equation (7).

$$GI = (LN^2 + 2.76 \times CN^2)^{1/2} \quad (7)$$

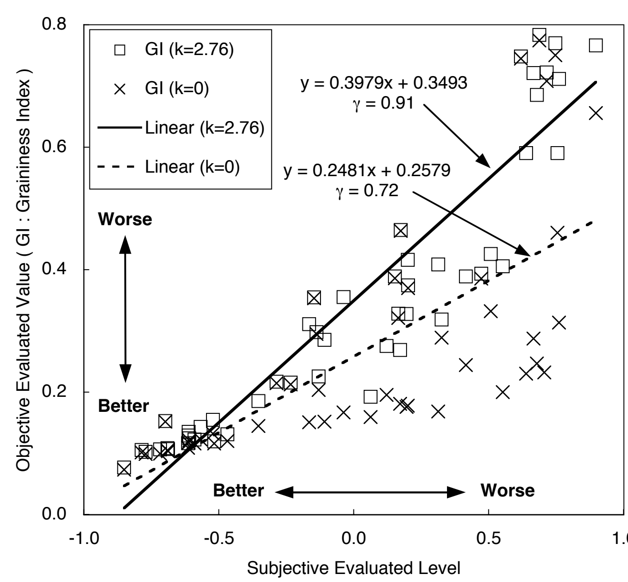

Figure 4. Relationship between GI and the subjective evaluated level. When k=2.76, the correlation coefficient becomes the largest value.

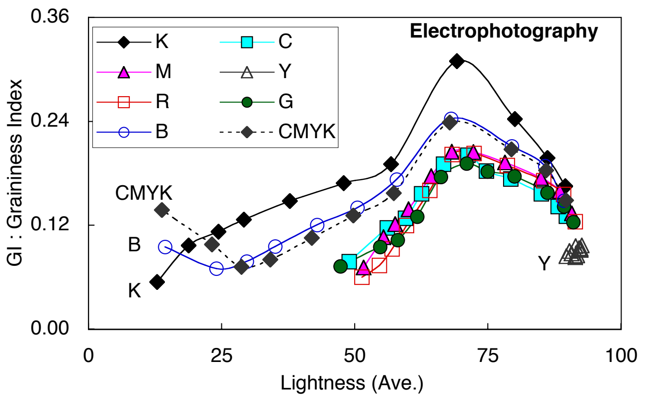

Figure 5. GI plotted versus the average lightness according to each color (Electrophotography). K, C, M, Y, R, G, B, and CMYK, denote Black, Cyan, Magenta, Yellow, Red, Green, Blue, and Process Black, respectively.

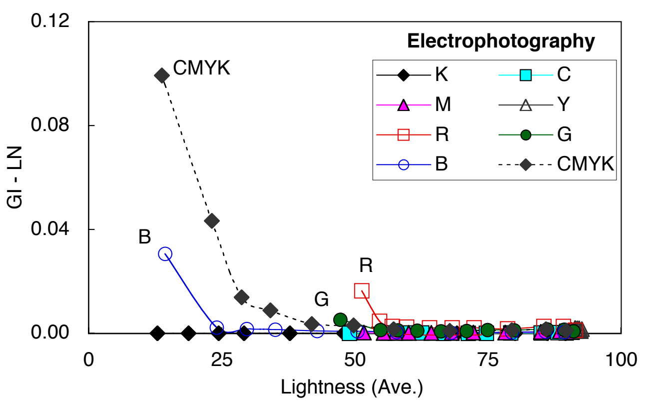

Figure 6. The difference between GI and LN plotted versus the average lightness according to each color (Electrophotography).

Application Results and Discussion

Electrophotography

We applied this objective evaluation model to the electrophotography image, which was printed out by a color printer with 256-tone levels and with resolution of 400 dpi (dots/inch). The results are shown in Figure 5. In this graph, we evaluated 88 patches which consist of 11-step scales for primary colors (C, M, Y, K), secondary colors (R, G, B), and process black (CMY or CMYK), and the GI for each patch are plotted versus the average lightness. In addition, the differences between GI and LN are similarly plotted in Figure 6, and you can see the influence of CN for each lightness level. LN and CN, are the metrics indicating the perceived noise for brightness and for chromatic component, both of values become larger as the perceived color noise increase. GI is basically expressed by the square root of the sum of squares for LN and CN, and it becomes larger as they increase.

As shown in Figure 5, the GI indicates the largest value when the image is just printed with primary K. Because its coloring material has the highest optical density compared with that of C, M, and Y, and the contrast between dots and

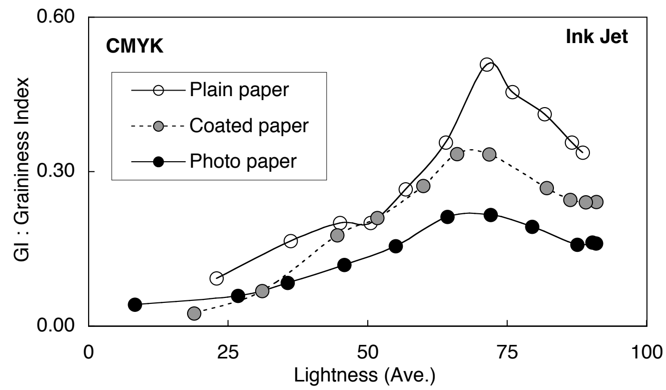

Figure 7. GI for process black (CMYK or CMY) patch images plotted versus the average Lightness according to each paper (Ink Jet).

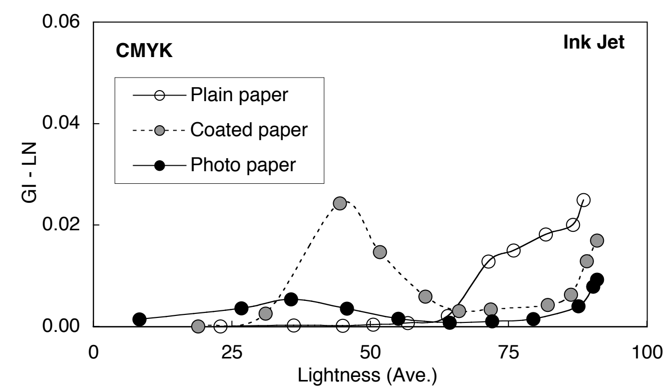

Figure 8. The difference between GI and LN plotted versus the average lightness according to each paper (Ink Jet).

the background, or paper, becomes largest. For this reason, the LN indicates larger than that of the other colors. However, it is a primary color, so that the CN hardly influences for the whole lightness range as shown in Figure 6. On the other hand, in case of process black, of which image is printed with 3 or 4 coloring materials, the GI indicates smaller than that of primary K, if their average lightness were the same. This is because the background of paper is further concealed compared with the case of primary K, and the amount of perceived brightness fluctuation would decrease. However, in the shadowy range, the GI for primary K is smaller oppositely compared with the process black. This phenomenon is due to the influence of CN as shown in Figure 6, and similar phenomena appear in the secondary colors; R, G, and B.

In addition, as shown in Figure 6, for these patch images, the LN is almost dominant for GI in the highlight range, in which our sensitivity for graininess is considered to become high. In this range, the isolated dots are printed with a fine screen ruling, 200 lines/inch, so that they are perceived as the brightness fluctuation, although printed with several coloring materials. In the human visual system, our perception is more sensitive to brightness fluctuation than chromatic one in the case when a fine screen image is printed, and the above-mentioned result could explain well our perception for color noise.

Moreover, as shown in Figure 5, there is a tendency to indicate the GI for B (C+M) a little larger than that of each color; C, M, R, and G. B (C+M) has a wide lightness range from highlight to shadow, compared with the other colors (C, M, R, G). In other words, the mixed coloring material B (C+M) has higher optical density than the other colors. Therefore, in the range where the influence of CN can be disregarded, the characteristic of GI is roughly in proportion to the optical density of its coloring material.

Ink Jet

Figure 7 shows the difference in GI according to paper types. It is clear that the paper types result in a large difference. Figure 8 shows the differences between GI and LN. The difference, GI – LN, increases in the highlight range, and also in the middle range for this model of ink jet. This tendency is quite different from that of electrophotography, which shows the difference increases in the shadowy range. This ink jet reproduced the images with relatively rough dots by Error Diffusion with resolution of 300 dpi. For this reason, although our sensitivity for chromatic fluctuation is lower than that of brightness, the fluctuation for chromatic component is relatively perceived with ease.

Comparisons with Silver Halide

For process black patch images (strictly speaking, the following silver halide is just printed with monochrome), we evaluated the GI on several printing types, which include silver halide, electrophotography, ink jet, offset, thermofusible ink transfer, and thermal dye transfer. The results are shown in Figure 9. This silver halide image is usually used as a test chart, and is almost regarded as an ideal one with high image quality. Nothing can compare with this silver halide image denoted the bottom in this figure, and the nearest one is thermal dye transfer. Then come thermofusible ink transfer, offset, ink jet, and electrophotography in that order. The image of this ink jet is printed on the special photo paper with the mode of so-called "photo quality print". For each point of the average lightness, approximately 70, where the GI becomes the largest value, the GI for this ink jet showed a little smaller, or better, than the electrophotography printed on the plain paper. Actually, there exist some ink jet printers, which showed a higher quality of graininess than this model of ink jet.

Figure 10 shows their spatial frequency characteristics after having multiplied by VTF to their WS for lightness, for each patch image of which average lightness is approximately 70. The characteristic of silver halide drawn below does not have a peak, or is featureless. On the other hand, the offset and the thermofusible ink transfer were printed with 175 lines/inch, and the electrophotography was printed with 200 lines/inch, so that they have the corresponding peaks respectively. The ink jet printed by Error Diffusion has no distinctive peak. The area of integration for each frequency characteristic corresponds to the LN. That is to say, keeping this area as small as possible leads to decrease, or improvement of LN. It is important that, as shown in Figure 10, the LN is not always in proportion to the printed resolution. For example, the

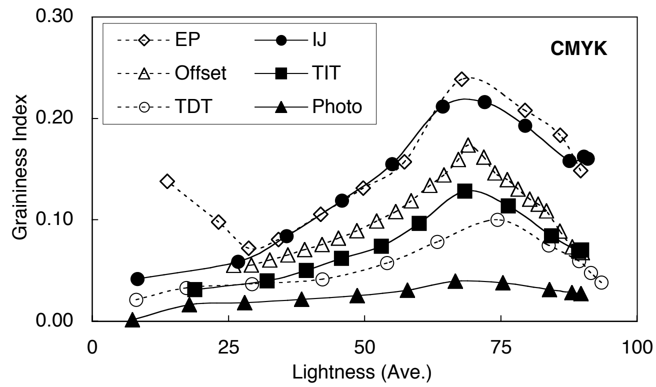

Figure 9. GI for process black (CMYK or CMY) patch images plotted versus the average lightness. EP, IJ, TIT, TDT and Photo, denote Electrophotography, Ink Jet, Thermofusible ink transfer, Thermal dye transfer, and Silver halide, respectively.

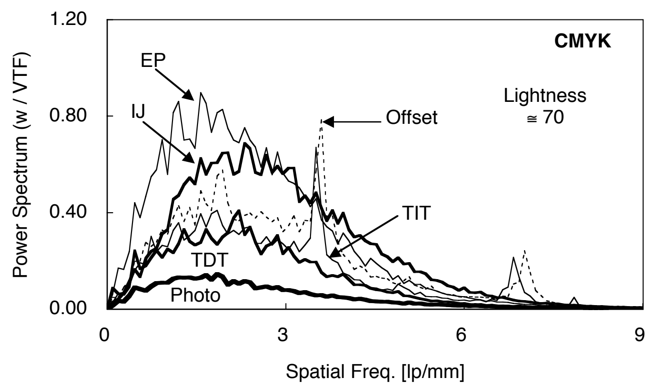

Figure 10. The spatial frequency characteristics with VTF for process black (CMYK or CMY) patch images, of which average lightness is approximately 70 respectively.

area of electrophotography is largest although it is printed with the finest screen ruling in this evaluated group. Therefore, it is necessary to decrease noise especially in the low frequency range, in which the VTF corresponding to our visual sensitivity has its peak.

Conclusions

For color images, the lightness noise LN is estimated from the brightness component, and the chromatic noise CN is estimated from the chromatic components, or metric chroma and hue-angle. By trying a subjective evaluation experiment with the method of paired comparisons by Scheffé, we optimized our evaluation model to predict the graininess index, GI, which basically calculated from the square root of the sum of squares for these two noise, or LN and CN. As a result, a high correlation coefficient of 0.91 is obtained between the subjective evaluated levels and the optimized GI.

Using this optimized GI, we investigated the image quality of graininess for several printing types of image. Nothing can compare with silver halide, the image of which is a synonym for photo quality. The graininess for ink jet, which has been remarkably improved lately, certainly surpasses that of electrophotography. However, paper types make a large difference in image quality, and especially in the case when printed on plain paper, it is common knowledge that performance will greatly decrease.

In consideration of the application results, the brightness fluctuation is more sensitive than the chromatic one in the highlight range, and the chromatic fluctuation influences gradually towards the shadowy range, with the exception of the case when a rough screen image is printed. These phenomena could explain well our perception for graininess on color images.

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