An Improved Multilevel Error Diffusion Method

Susumu Sugiura and Takeshi Makita
Product Technology Development Center, Canon Inc., Tokyo, Japan

Abstract

The recent technological improvements of inkjet printers have been significant, and these printers are now finding widespread acceptance in offices and homes. One of the most important factors for this acceptance has been the achievement of high image quality. There are two major approaches to improving the image quality of inkjet printers. The first is to increase the inkjet head's resolution. The second is to develop a multilevel error diffusion method using multiconcentration inks. We have opted for the second approach and have been able to improve the halftoning method by exploiting some new insights we have gained. The conventional multilevel error diffusion method generates contouring at the locations in which the original picture's density is close to the density of the multiconcentration inks, because at those points no error occurs. In this study we analyze the conventional methods to explain this contouring. On the basis of this analysis we propose a new, improved multilevel error diffusion method. To verify our theory experimentally we have used a silver halide printer to simulate a printer based on our new technology. We have evaluated the image quality of our new method with that of the conventional method and found our method superior.

Introduction

To design the specifications of a printer it is very important to know the performance of the human visual system. According to Roetling,[1] the number of levels that a person with normal vision can discern is given by Eq. 1:

$$L = 1010(\exp[-0.138(5\omega)](1 - \exp[-0.l(5\omega)])) + 1, \qquad (1)$$

where L = number of levels discernible and ω = spatial frequency (cycles/mm).

The number of tones that can be rendered on a printer using multilevel error diffusion halftoning is given by Eq. 2:[1,2]

$$N = [(\mathrm{res}/2)^2(2^n - 1)]/(\omega^2 + 1), \qquad (2)$$

where

N = number of tones that can be rendered;
n = printer's number of primary gray levels;
ω = spatial frequency (cycles/mm);
res = printer's resolution (dots/mm).

Our design goal is to approach the performance of the human visual system. This means that the number N of tones that can be rendered (Eq. 2) should approach the number L of discernible levels (Eq. 1). Examining Eq. 2, we note that there are two potential parameters: the resolution, res, and the number of gray levels, n. To vary the first parameter we would have to develop a new inkjet head. We have chosen to vary the number of gray levels, because it is easy to design an inkjet printer with such a capability.[2]

Survey of Conventional Multilevel Error Diffusion Methods

Katoh, Arai, and Yasuda[3] reported in 1973 on a study of multilevel error diffusion methods. Their basic idea was to switch the threshold levels in the error diffusion method, depending on the density of the input data relative to multiconcentration inks. Their proposal is very easy to implement on an inkjet printer, but it has the drawback of causing contouring. This contouring is substantial at those locations of the image where gray levels are close to a density for which an ink is available. In the other locations of the image their method renders the images with excellent quality. In this study, we designate their method as "ME2."

More recently, Ochi[4] has addressed this problem. Ochi tries to reduce the contouring, improving Katoh, Arai, and Yasuda's method by iterating the error diffusion with a layered structure. In his method, if there are N (where $N = 2^m$) concentration levels, the iteration is repeated ($m + 1$) times. Whereas this improved method succeeds in reducing the contouring, the deviation is increased in uniform density areas. In this study, we designate Ochi's method as "ME3."

Analysis of Contour and Deviation in Multilevel Error Diffusion

For simplicity, we assume an ideal printer in which the printed dots do not overlap. We consider a pixel in the halftoned image and study the relation between the expected value of the gray level and the variance or deviation. The gray level determines the tone reproduction; the deviation is a measure of contouring. The expected value is estimated by the mean of the halftoning image data. The variance or deviation is estimated by the standard deviation.

In this section we compare the mean value and standard deviation for two ideal printers. The first printer can produce dots at 3 levels—0, 0.5, and 1—on a normalized density scale. The second printer is a conventional binary printer, producing dots of density levels 0 or 1 on the same scale.

If the arbitrary halftoning image data are expressed as g_i and the mean of its image data is expressed as g_1, then we define the expected values $E(g_i) = g_1$.

In the full normalized range of gray levels ($0 \leqq g_i \leqq 1$), the standard deviation can be expressed as follows:

$$\begin{aligned}\sigma_{g1}^2 &= \frac{1}{N}\sum_i (g_i - g_1)^2 = \frac{1}{N}\sum_i g_i^2 - \frac{2g_1}{N}\sum_i g_i + g_1^2 \\ &= \frac{1}{N}\sum_i g_i - g_1^2.\end{aligned} \tag{3}$$

In the case where the image is halftoned to a 3-level image, g_i can be substituted by P_i, where $P_i = \{0.0, 0.5, 1.0\}$.

First, we consider the lower half of the tonal range. For $0 \leqq g_i \leqq 0.5$, Eq. 3 becomes Eq. 4:

$$\begin{aligned}\sigma_{g1}^2 &= \frac{1}{N}\sum_i (0.5p_n)^2 - g_1^2 = \frac{0.25}{N}\sum_i P_i - g_1^2 \\ &= g_1(0.5 - g_1) \\ \sigma_{g1} &= \sqrt{g_1(0.5 - g_1)}.\end{aligned} \tag{4}$$

Second, we consider the upper half of the tonal range. For $0.5 \leqq g_i \leqq 1.0$,

$$E\{g_i\} = \frac{1}{N}\sum_i (g_i + 0.5) = g_2.$$

In the range $0.5 \leqq g_i \leqq 1.0$, the standard deviation can be expressed as follows:

$$\sigma_{g2}^2 = \frac{1}{N}\sum_i \{(0.5 + g_i)^2 - g_2\}^2 = \frac{1}{N}(g_i + 0.5)^2 - g_2^2. \tag{5}$$

On the other hand, in the upper tonal range,

$$\frac{1}{2}\left(\frac{1}{N}\sum_i P_i\right) = g_2 - 0.5. \tag{6}$$

From Eqs. 5 and 6,

$$\sigma_{g2} = \sqrt{(g_2 - 0.5)(1.0 - g_2)}. \tag{7}$$

These relations for the image data mean value and standard deviation are based on 3-level halftoning, i.e., P_i has only 3 kinds of data, 0.0, 0.5, and 1.0. In the case of black-and-white 2-level halftoning, the relation will be as follows:[5]

$$\sigma_{ed} = \sqrt{g_{ed}\,(1.0 - g_{ed})}. \tag{8}$$

Figure 1 shows the relationships based on Eqs. 4, 7, and 8. In this figure, the horizontal axis shows the deviation. Examining this figure, we can easily understand why contouring occurs in an image halftoned with multilevel error diffusion. The standard deviation is zero at gray levels for which an ink density is available. Between two densities for which ink is available, the standard deviation first increases monotonically from zero to a maximum at the center of the range, then decreases monotonically to zero. Behavior wherein the standard deviation reaches zero at intermediate tone levels is the cause of the contouring phenomenon visible in images rendered with conventional multilevel error diffusion methods. Our strategy is to smooth the standard deviation so that it is not zero at intermediate gray levels.

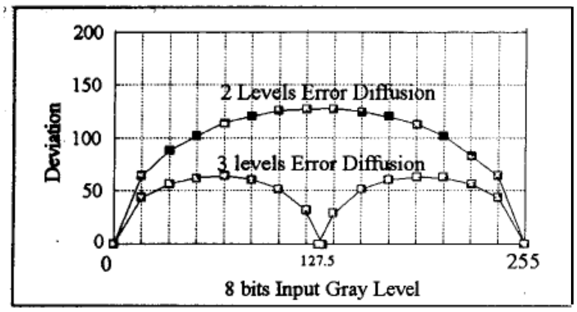

Figure 1. Characteristics of theoretical deviation.

Measurement of the Pixel Deviation in Conventional Multilevel Error Diffusion Methods

Under the condition that there is no overlap between printed dots, we measured deviation and linearlity obtained with conventional error diffusion methods[6] and multilevel error diffusion methods.

In Figure 2 we compare the deviation and tone reproduction linearity for three error diffusion methods.

- ERD_Lin and ERD_Dev show the characteristics of both linearity and deviation in the conventional 2-level error diffusion method.
- ME2_Lin and ME2_Dev show Katoh, Arai, and Yasuda's multilevel error diffusion method.
- ME3_Lin and ME3_Dev show Ochi's multilevel error diffusion method.

For the deviation, from Fig. 2 we can see that both multilevel error diffusion methods are better than the conventional bilevel error diffusion method. When we compare the two multilevel error diffusion methods, ME2 is better than ME3 both in the deviation uniformity and in the tone reproduction linearity. However, when we compare visually images printed with the two methods, we note that ME3 has less contouring than ME2.

Both methods have advantages and disadvantages. Therefore we tried to develop a new multilevel error diffusion method in which we take into account deviation, linearity, and contouring.

A New Multilevel Error Diffusion Method

Figure 3 shows the conceptual diagram of our new multilevel error diffusion method. In this figure, the curves show the following data:

1. Characteristic shape of deviation with the conventional error diffusion method;
2. Deviation with multilevel error diffusion methods based on Eqs. 4 and 7;
3. Desired characteristic curve of deviation.

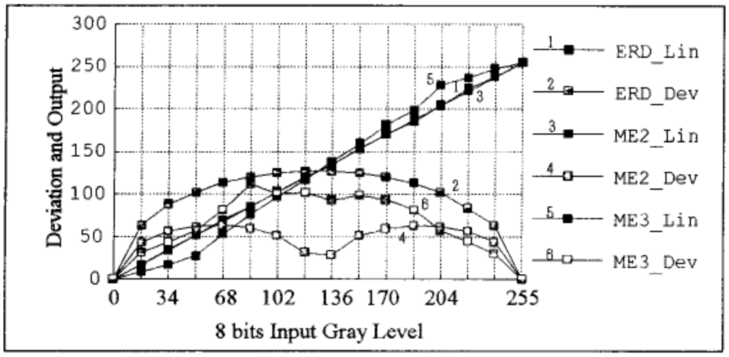

Figure 2.Characteristics of actual deviation and linearity.

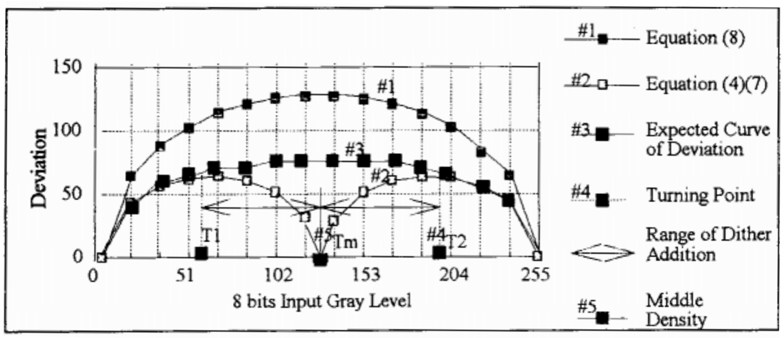

Figure 3. Basic concept of new multilevel error diffusion method.

If Curve 3 can be realized, the rendered image will be of very high quality in both the deviation and in linearity. To realize this characteristic shape, we add noise to increase the deviation around the density printed by the ink of intermediate density, thus avoiding a zero. The added noise is increased from the lower turning point (T1 in Fig. 3) to the middle density point Tm. The noise is then reduced from the middle density point Tm to the upper turning point T2.

Figure 4 shows how noise is added in the range from the lower turning point to the upper turning point. In this figure, the low turning point is $th - m$ and the upper turning point is $th + m$, where th is the density Tm printed by the second ink, and m is a parameter determining the noise magnitude. The value of m is determined experimentally. The label exy refers to the input image data located at (x,y), and Pxy refers to the output image data at the same location.

Figure 5 shows a diagram of our implementation realizing the new multilevel error diffusion method. In this figure, noise is added, using a 4×4 dither matrix as deicribed below. To preserve the density between the original image and the processed one, the error diffusion method is applied in a 4×4 block. The diffusion matrix size is smaller than the conventional one because if the diffusion matrix is large—such as 3×5—the added noise will be averaged and will not reduce contouring.

The noise is added to the original image, and then the image data are processed, using Katoh, Arai, and Yasuda's method, ME2. There are three branches, depending on input data value. When exy is larger than $(th + m)$ or smaller than $(th - m)$, the output data remain exy, i.e., no compensation occurs. In the case $(th - m) < exy < (th + m)$, noise is added to the input value, i.e., $(exy + noise)$ is output. This compensation consists of clustered dither noise.

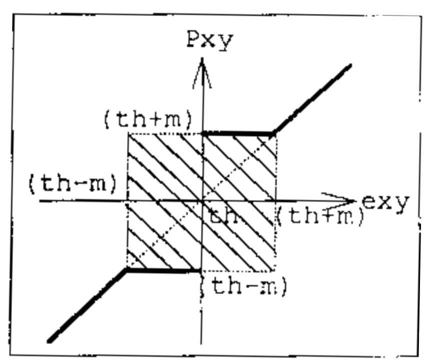

Figure 4. Noise-adding areas.

As can be seen in Fig. 5, hardware implementation of various steps (error diffusion, dithering, and conditional branching) can be easily carried out by conventional technologies.

Figure 6 shows the changes of the characteristic curves for deviation and linearity, depending on the magnitude parameter m, based on our new multilevel error diffusion method. In this figure, 36_Dev denotes the characteristic curve of the deviation for m = 36 and similarly 40_Lin refers to the characteristic linearity with m = 40. Varying the parameter m from 32 to 42, we measured the deviation and selected m = 38 as the most suitable value because it yielded the most uniform deviation. We designate our new method as "ME4."

Comparison of Image Quality

The test chart we used for assessing image quality consists of two geometric regions and one pictorial photograph:

1. 16 patches;
2. Continuous-tone scale;
3. "Garden" chart with Japanese character and two photos.

We produced simulated samples processed with the conventional error diffusion method (ERD), Katoh, Arai, and Yasuda's method (ME2), Ochi's method (ME3), and our new method based on m = 38 (ME4). For the simulation we used a silver halide continuous-tone printer.[7] Plate 0 is a rendition of the original test chart. Plates 1 to 4 show the four respective simulations.

Because of the limitations due to halftoning of the plates for publication, it is necessary to explain the differences in each quality.

In ERD simulation granularity is very visible, in ME2 contouring occurs in the face of the woman, and in ME3 contouring disappeared but granularity increased more than in ME2. In ME4 simulation there is no contouring and granularity decrease to the same degree as in ME2.

The deviations and tone reproduction curves are shown in Fig. 7. From the point of linearity and deviation, ME3 and our ME4 are clearly superior. Furthermore, with regard to contouring, ME4 is superior to ME3. Visual judgment confirms that the sample rendered by the ME4 method is the best.

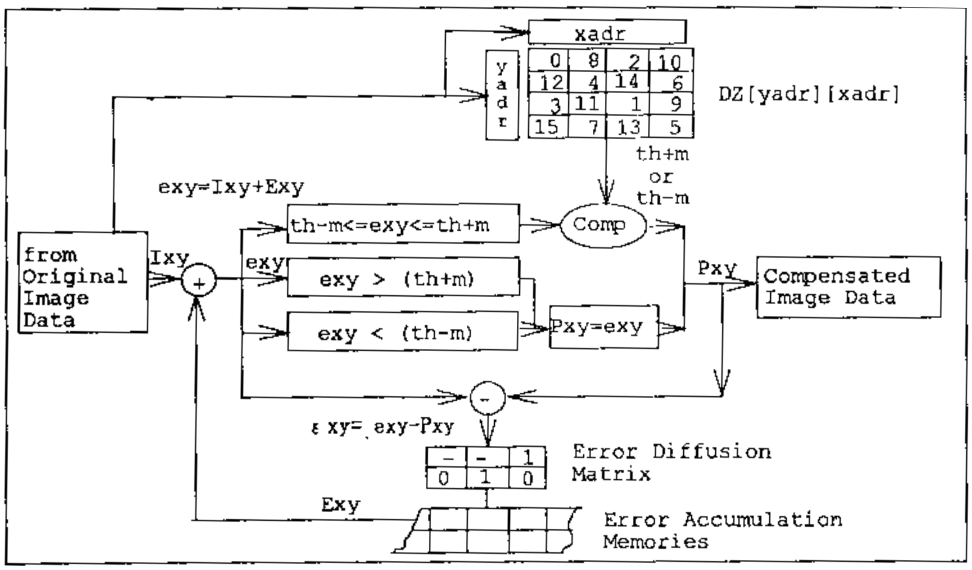

Figure 5. Block diagram for new multilevel error diffusion.

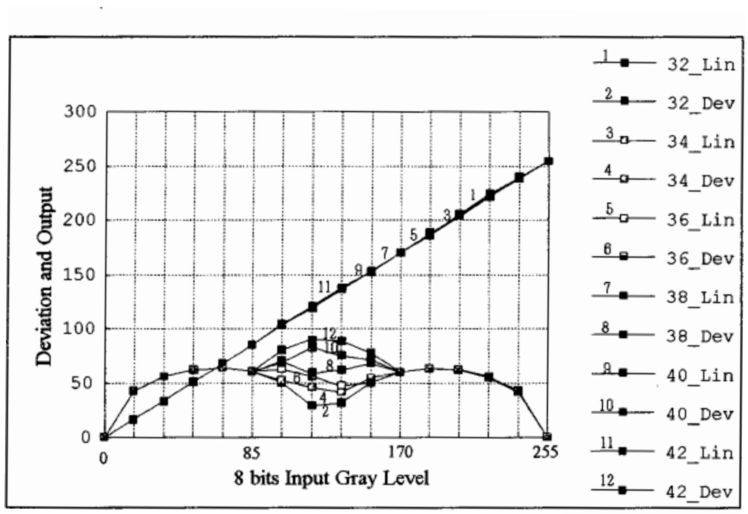

Figure 6. Characteristics of deviation versus m values.

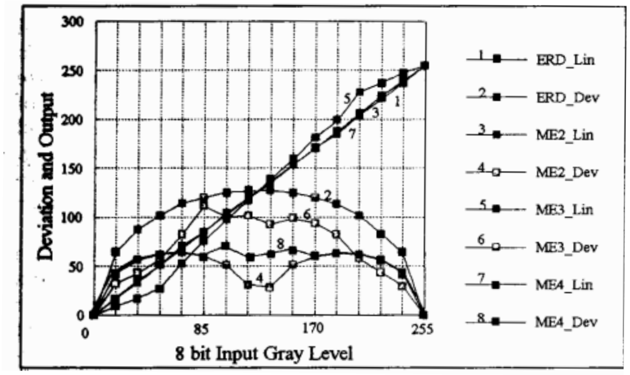

Figure 7. Comparison of deviation and linearity.

Conclusions

We have presented a new multilevel error diffusion algorithm that achieves high image quality. Image quality is measured quantitatively and subjected to visual judgment. The main features of our new multilevel error diffusion method are that it:

1. Reduces contouring;
2. Keeps the deviation small;
3. Preserves the image density between original and processed images; and
4. Provides a very simple algorithm suited for hardware implementation.

Acknowledgments

We acknowledge the support of Dr. Giordano B. Beretta of the Hewlett-Packard Laboratory in the United States, for checking our English.

References

1. P. G. Roetling, Visual performance and image coding, Image Processing, *SPIE/OSA* **74**: 195–199 (1976).
2. T. Kobayashi and S. Sugiura, An image quality simulation for binary and multilevel images with quantization and resolution, *Japan Hardcopy 89*, pp. 241–244 (in Japanese).
3. S. Katoh, Y. Arai, and Y. Yasuda, Multilevel error diffusion method, *National Conference of Communication, Department in Showa 53 Year, Society of Electronic Communication in Japan (1973)*, p. 504 (in Japanese).
4. H. Ochi, High quality multilevel error diffusion method with layered structure, *140th Research Meeting for Image Processing and Communication, Society of Image Electronics in Japan (1994)*, pp. 17–20 (in Japanese).
5. R. Ulichney, *Digital Halftoning*, The MIT Press, Cambridge, MA, 1987.
6. R. W. Floyd and L. Steinberg, Adaptive algorithm for spatial gray scale, *SID Int. Sym. Digest of Tech. Papers*, 1975, pp. 3637.
7. K. Nagashima, Full-color digital laser printing system based on photothermographic material, *Proceedings IS&T/SEPJ 9th Intemational Congress on Advances in Non-Impact Printing Technologies/Japan Hardcopy '93*, Yokohama, 1993, pp. 497–500.

❋ Previously published in the *Journal of Imaging Science and Technology* **38**(6) pp. 545–551, 1994.

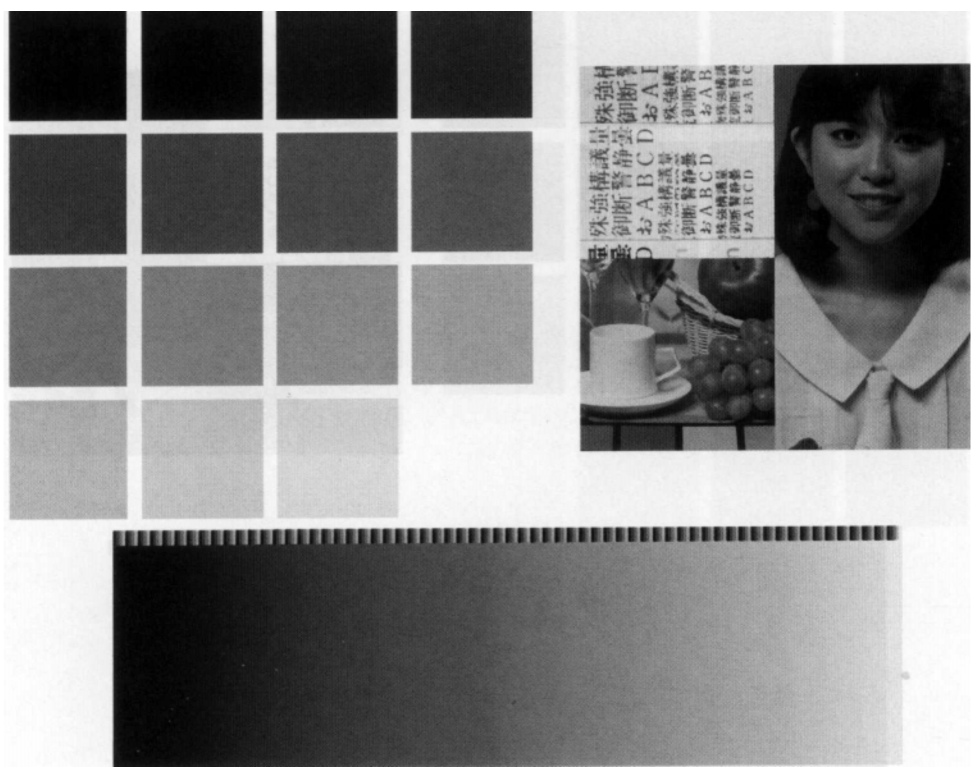

Plate 0. Original test chart.

Plate 1. ERD simulation

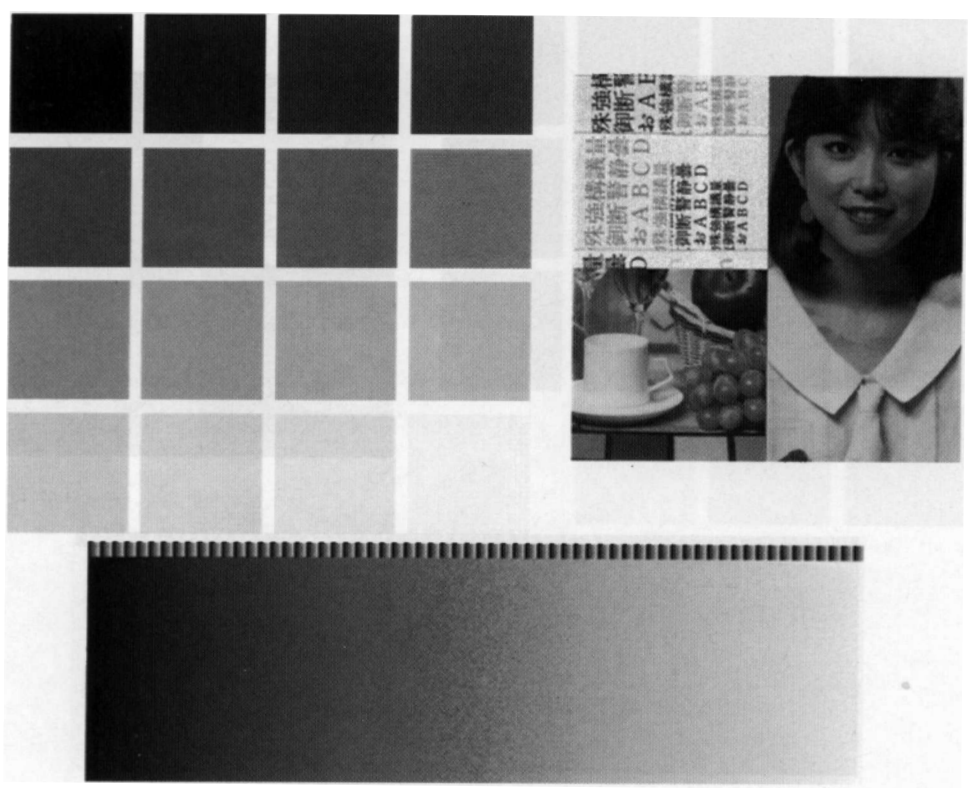

Plate 2. ME2 simulation

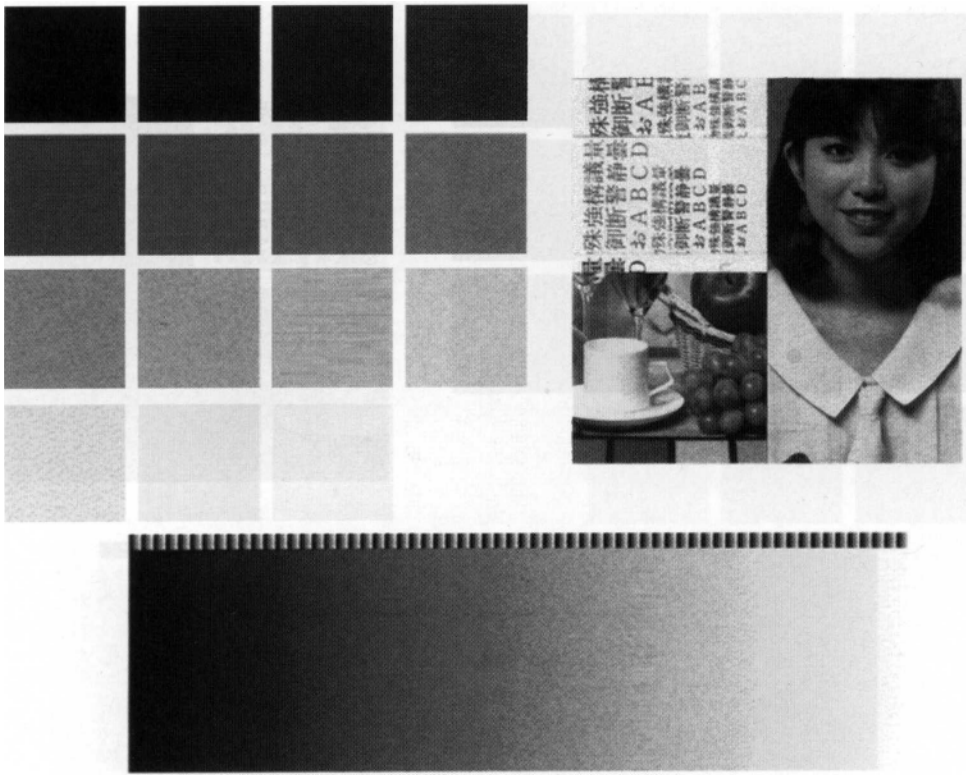

Plate 3. ME3 simulation

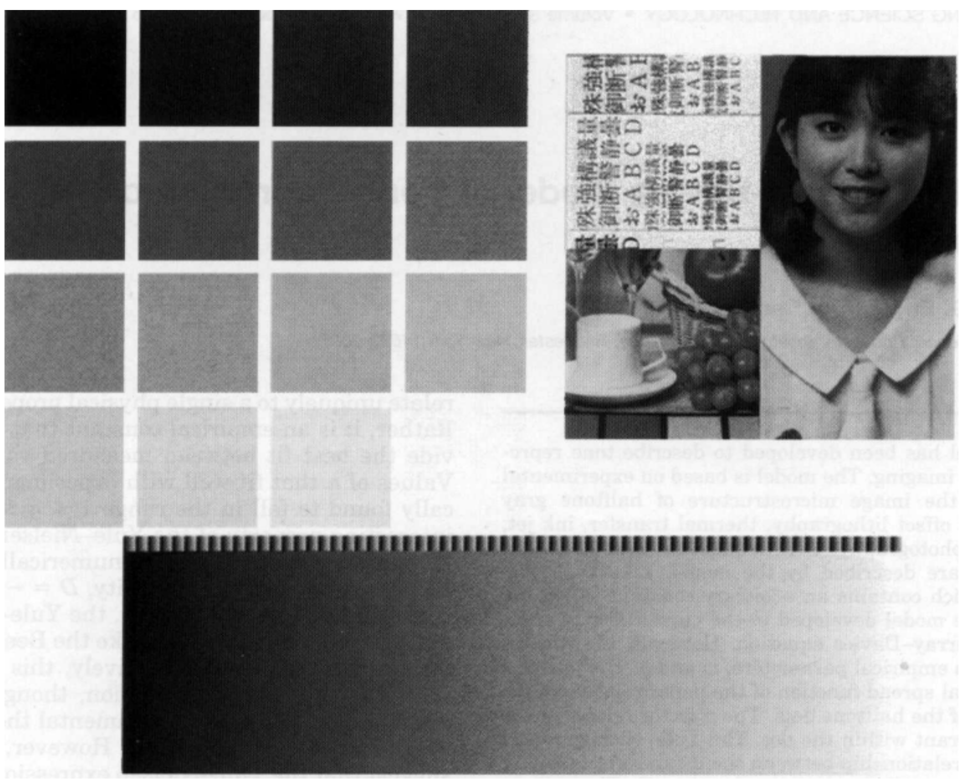

Plate 2. ME4 simulation