Improvement of Low Gray-Level Linearity using Perceived Luminance of Human Visual System in PDP-TV

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Abstract — *One of the factors deteriorating image quality of PDP-TV is the low gray-level contour occurring mainly due to inverse gamma correction. From the viewpoint of human visual perception, the low gray-level contour becomes more serious because of the nonlinear output luminance of PDP at low gray-levels. In this paper, a modified inverse gamma correction method and a gray-level linearization technique considering human visual perception are proposed for enhancing image quality at low gray-levels*[1].

Index Terms — inverse gamma correction, low gray-level linearity, plasma display panel.

I. INTRODUCTION

Cathode ray tubes (CRTs) convert a video signal to light in a nonlinear way [1], because the electron gun it contains is a nonlinear device. To compensate for this effect, the gamma correction is applied to the video signal so that input-output response is linear. In other words, the transmitted signal is deliberately distorted so that, after it has been distorted again by the display device, the viewer sees the correct brightness. However, a plasma display panel (PDP) has a linear output luminance response to a digital-valued input [2]. Therefore, further adjustment needs to be made to the digital-valued inputs, referred to as inverse gamma correction, where several gray-levels are merged into a fixed output luminance-level, especially for low input signal levels up to 50. This merging effect causes low gray-level contours that are abrupt changes of brightness in the visual gradation pattern [3]. Figure 1 shows the input-output characteristics of a TV broadcasting system.

There have already been various attempts to suppress low gray-level contours in a PDP. A multi-luminance-level subfield method [4] and an error diffusion method based on the light emission characteristics of a PDP [5] were recently developed to solve this problem. However, these methods did not consider the effect that the emitted luminance during a reset and address period influences the perceived luminance, which is defined as the luminance actually recognized by human eyes. Therefore, they often fail to reduce the false contours in dark areas effectively because of the nonlinear perceived luminance characteristics to an input gray-level. In the research of Yamada et al. [6], they try to make the increments of the perceived luminance identical to all the gray-level steps by adopting the contiguous 208-subfield scheme. In other words, they designed the nonlinear light emission patterns for gray-levels so that the perceived luminance is linearly proportional to the increments of gray-level considering human visual perception, which is called the gray-level linearity. Although this method is promising, it cannot be applied to the most commercial PDPs using the ADS (address and display period separated) driving scheme.

In this paper, we propose a new method for improving the gray-level linearity considering human visual system (HVS). This converts the gamma-corrected input video signal based on signal processing technique into the nonlinear signal so that the viewer perceives linearly the luminance on a PDP. In the research, this conversion is carried out by using the look-up table, which is concretely formulated based on the light emission characteristics of a PDP. Then, the converted signal is applied to the system using the ADS driving scheme to visually verify that the proposed method can enhance image expression at low gray-level.

The remainder of this paper is organized as follows. Section II outlines the modeling of the output luminance and light emission characteristics of a PDP using the ADS driving scheme. Section III explains the modified inverse gamma correction and the gray-level linearization technique, which can improve the low gray-level linearity based on human visual perception. In Section IV, the performance of two proposed methods is visually evaluated by employing the conventional 8-subfield system and the 9-subfield system in [5]. Finally, Section V gives some conclusions.

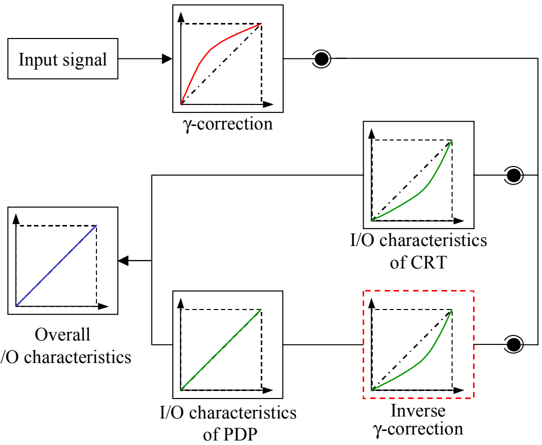

Fig. 1. Input-output characteristics of TV broadcasting system.

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II. LIGHT EMISSION CHARACTERISTICS OF PDP

In a CRT, the intensity of the light emission is analog-controlled by the strength of the electron beam striking the phosphor-coated screen. In contrast to the expression of a gray-level in a CRT, the gray scale of a PDP using the ADS driving scheme is expressed by adjusting the number of sustain pulses. Generally, to express 256 gray scales, the TV field (16.7 ms) is divided into 8 subfields and the output luminance-levels for each subfield are 2^n ($0 \le n < 8$) and each subfield consists of the reset, address, and sustain periods. As such, the modeling of the output luminance of PDP [5] is expressed as

$$\begin{aligned} B &= L_D + L_R \\ &\cong \sum_i \omega_i l_i + L_R \\ \omega_i &= \begin{cases} 1 & if\ subfield\ i = ON \\ 0 & if\ subfield\ i = OFF \end{cases}, \end{aligned} \quad (1)$$

where B is the luminance value measured on the actual PDP using a color analyzer CA-100, L_D is the luminance value during a sustain period, L_R is the luminance value during a reset and address period, of which the effect has not been considered properly in the traditional inverse gamma correction, and l_i is the luminance value measured for the i-th subfield period. Now, the luminance-level Y is defined as

$$Y = \frac{B - L_R}{L_{MAX} - L_R} \times G_{MAX} , \quad (2)$$

where L_{MAX} is the maximum luminance of the actual PDP. G_{MAX} is the expressible maximum gray-level in a PDP and is generally 255.

To measure the output luminance-levels of an actual PDP, a 4-inch test panel was used. The gas used in the 4-inch test panel was an He-Ne(7:3)-Xe(4%) mixture at a pressure of 400 Torr, plus the driving conditions were a sustain voltage of 180 V, sustain frequency of 200 kHz, address voltage of 60 V, and reset voltage of 390 V. The output luminance of the PDP was measured using the CA-100. Table I shows the measured output luminance in 4-inch test panel. The measured luminance is used to calculate an expressible luminance-level on a PDP by the modeling of the output luminance of the PDP.

TABLE I
MEASURED OUTPUT LUMINANCE VALUES IN 4-INCH TEST PANEL BY CA-100.

Subfield number	Number of sustain pulse pair	Measured luminance l_i $[cd/m^2]$	Luminance-level B
SF1	2	3.30	1.912
SF2	4	5.2	3.013
SF3	8	9.0	5.216
SF4	16	16.5	9.562
SF5	32	30.8	17.85
SF6	64	59.3	34.37
SF7	128	109.8	63.63
SF8	256	203.8	118.1

III. GRAY-LEVEL LINEARIZATION BASED ON HVS

The received gamma-corrected analog video signal x is separated into red, green, and blue channels in the signal-processing unit. In addition, each color signal is converted into 8-bit digital signal, and inverse gamma correction formulated below is adopted, respectively [7].

$$Y = z(x) = k \times \left(\frac{x}{G_{MAX}} \right)^{\gamma} , \quad (3)$$

where γ represents the gamma value of 2.2 and k denotes the maximum gray-level representing the white point. Y is the analog output luminance-level for displaying an input gray-level. The output luminance B of the PDP module is determined by Eq. (4) with the output luminance-level defined in Eq. (3).

$$B = f(x) = (L_{MAX} - L_R) \frac{Y}{G_{MAX}} + L_R . \quad (4)$$

The relation between the perceived luminance P and the output luminance B [7] is experimentally determined and given by

$$P = g(B) = cB^{\beta} , \quad (5)$$

where $c = 2.29$ and $\beta = 0.382$. The signal flow is represented in Fig. 2.

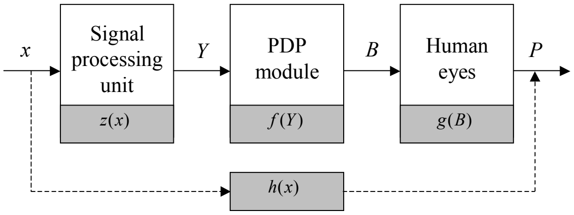


Fig. 2. Block diagram for signal flow

Figure 3 shows the relationship between the input gray-level of the PDP and the perceived luminance using the inverse gamma correction method with gamma value of 2.2. As defined in [6], an ideal display should have the linear perceived luminance characteristics to an input gray-level. As shown in Fig. 3, however, the relationship between them is nonlinear. The perceived luminance with $\gamma = 2.2$ is seen to be deviated from the ideal perceived luminance line theoretically calculated. Especially, the slow increase of the perceived luminance with respect to the input gray-level 0 to 30 spoils the low gray-level linearity, which also causes the low gray-level contour due to the minute difference between the perceived luminance values. Namely, from the viewpoint of human visual perception, the low gray-level contour is quite serious because the output luminance of PDP does not guarantee the linearity at low gray-levels. That is mainly because a fixed amount of light L_R is always emitted during the reset and address period regardless of the input gray-level. For the ideal display, L_R is zero. However, L_R was about 1.2 cd/m^2 for the actual PDP due to the ADS driving scheme in the PDP.

There are two problems in Fig. 3(b). The first one is nonlinearity at low gray-levels because of the emitted luminance L_R during a reset and address period. The second one is that a number of gray-levels are merged into a fixed output luminance-level, especially for low input signal levels up to 50. These two problems are factors of low gray-level contour.

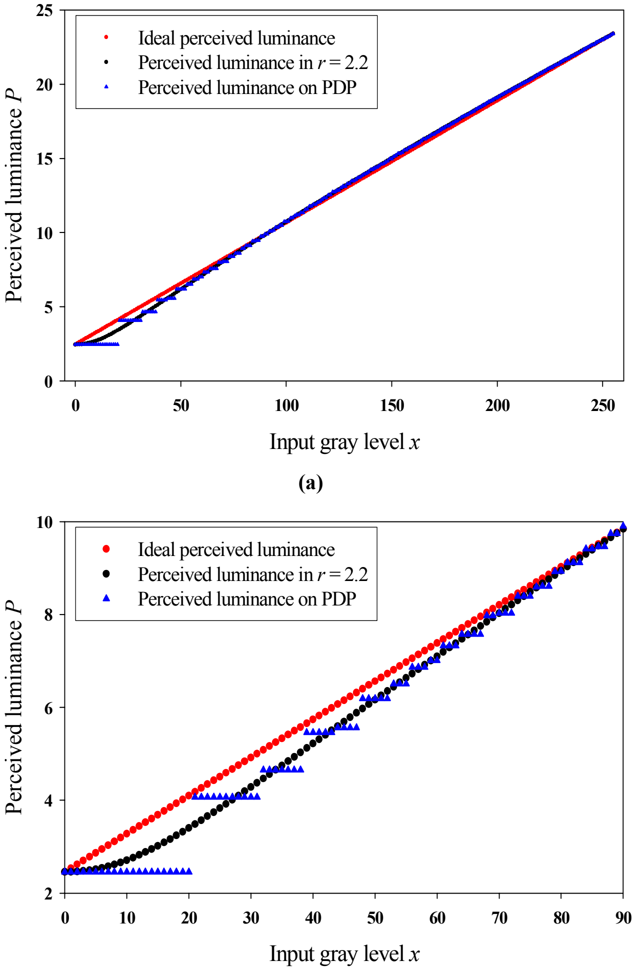
A. A. Modified Inverse Gamma Correction

In Eq. (5), the response of human eyes is not linear. At any given instant, human eyes are more sensitive to luminance changes in dark areas than to similar-sized changes in bright areas. Therefore, the effect of L_R needs to be minimized in low gray-level because that becomes much significant in dark areas. In the viewpoint of signal processing technique, raising the increasing rate of the output luminance will be a solution using $\gamma = 1.8$ at the range up to 90 in order to compensate for the nonlinearity of the perceived luminance at low gray-levels. Thus, Eq. (3) is modified as follows:

$$Y = \begin{cases} 25.792\left(\dfrac{x}{90}\right)^{1.8} & 0 \le x \le 90 \\ 255\left(\dfrac{x}{255}\right)^{2.2} & 90 < x \le 255 \end{cases} \qquad (6)$$

The resultant relationship between input gray-levels and perceived luminance on a 8-subfield PDP using the proposed inverse gamma correction method is shown in Fig. 4. Figure 4(b) shows the improved linearity comparing Fig. 3(b) at low gray-levels.

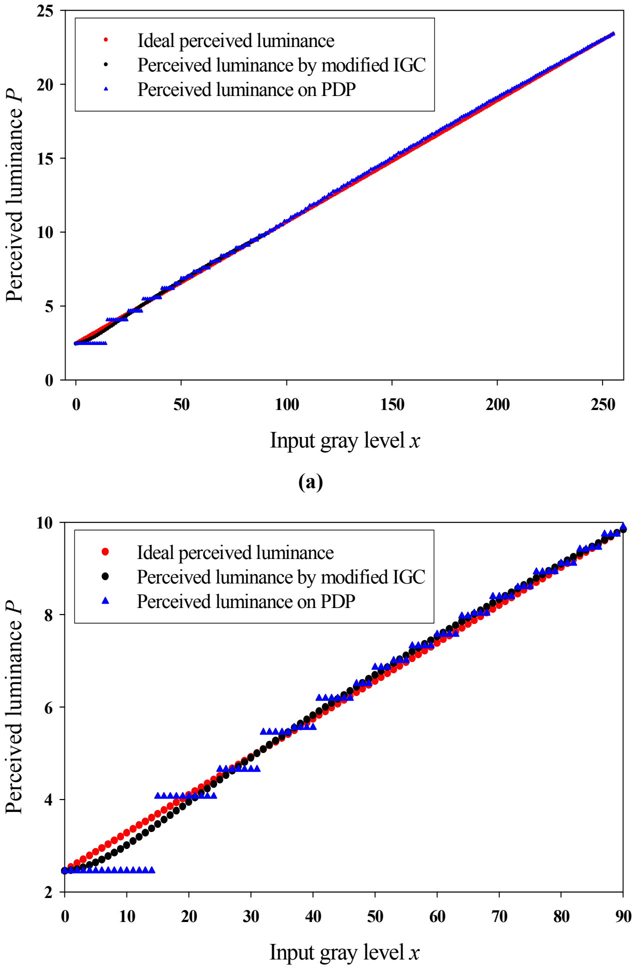
B. Gray-Level Linearization Technique Based on Human Visual Perception



(a)

(b)

Fig. 3. Relationship between input gray-level and perceived luminance on 8-subfield system with $\gamma = 2.2$ for input signals (a) up to 255 and (b) up to 90.



(a)

(b)

Fig. 4. Relationship between input gray-level and perceived luminance on 8-subfield system using modified inverse gamma correction for input signals (a) up to 255 and (b) up to 90.

In the proposed method, the function representing the signal-processing unit in Fig. 2 is defined using the parameters, which represent the light emission characteristics, and using the luminance response curve considering human visual perception. In Fig. 2, the transfer function $h(x)$ should be defined as a linear function so that the relationship between the input signal x and the perceived luminance P is linear. The transfer function $g(B)$ is determined as Eq. (5) by using the characteristics of human visual perception, and the transfer function $f(Y)$ is defined by the light emission characteristics of PDP. Thus, we can define $h(x)$ by formulating $z(x)$ using $g(B)$ and $f(Y)$.

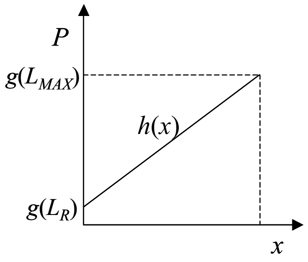


Fig. 5. Ideal perceived luminance response curve to input signal

Suppose that $h(x)$ is linear in the interval $0 \le x \le 255$. Then we should be able to formulate the perceived luminance P as

$$P = h(x) = mx + n ,$$

where m is the slope of the function $h(x)$ and n is the P-intercept of $h(x)$ in Fig. 5. Let $m = \{g(L_{MAX})\text{-}g(L_R)\}/G_{MAX}$ and n $= g(L_R)$. Then, from Eq. (5), m and n are defined as

$$m = \frac{c\left(L_{MAX}^{\beta} - L_{R}^{\beta}\right)}{G_{MAX}} \text{ and}$$

$$n = g(L_R) = cL_R^{\beta} .$$

Hence, the desired luminance-level can be formulated as

$$\begin{aligned} Y = z(x) &= f^{-1}\left\{g^{-1}\left(h(x)\right)\right\} \\ &= \frac{\left(\frac{m}{c}x + \frac{n}{c}\right)^{1/\beta} - L_R}{L_{MAX} - L_R} \times G_{MAX} \end{aligned} \tag{7}$$

TABLE II

PART OF LOOK-UP TABLE BY GRAY-LEVEL LINEARIZATION TECHNIQUE

x	$z(x)$	x	$z(x)$
0	0	20	1.97362
1	0.062895	21	2.11615
2	0.129171	22	2.26327
3	0.198897	……	……
……	……	254	252.657
19	1.83565	255	255

When the light emission characteristics of a PDP is determined, $z(x)$ in Eq. (7) can be represented as the look-up table as shown in Table II.

IV. EXPERIMENTAL RESULTS

The performance of the proposed linearization methods was evaluated by comparing the result images with those of the conventional inverse gamma correction with $\gamma = 2.2$, after applying to the conventional 8-subfield system and the 9-subfield system proposed in [5]. For the experiments, a new error measure was set up to quantify the error between the perceived luminance on the PDP and that on the ideal display. Generally, the eye's resolution is limited to roughly one minute of arc, a limitation that comes from the distribution of photoreceptors on the retina [8]. Therefore, human visual perception works based on the local mean luminance value of the surrounding area of a pixel, rather than a single luminance value. Thus, if an individual watches a 42-inch HDTV at a distance of 3 meters, the extent of a recognizable image will correspond to a 2 × 2 pixel size. As such, the proposed error measure in Eq. (9), which finds the error at position (i, j), is defined as the difference between the perceived luminance of the average luminance on the ideal display and that on the actual PDP to the extent of a 2 × 2 pixel size.

$$E_{i,j} = \sqrt{\left\{ P\left(\frac{1}{4}\sum_{k=0}^{1}\sum_{l=0}^{1} L_{ideal}^{i+k,j+l}\right) - P\left(\frac{1}{4}\sum_{k=0}^{1}\sum_{l=0}^{1} L_{PDP}^{i+k,j+l}\right) \right\}^2} , \tag{8}$$

$$E_{ave} = \frac{1}{MN}\sum_{i=0}^{M-1}\sum_{j=0}^{N-1} E_{i,j} . \tag{9}$$

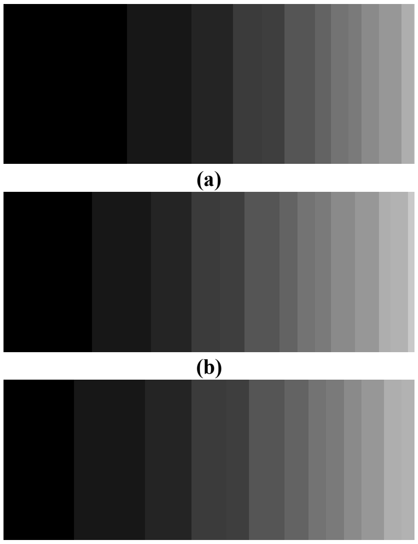
Here, L_{ideal} and L_{PDP} are luminance on the ideal display and actual PDP, respectively. $E_{i,j}$ is the error at the position (i, j) and E_{ave} is the average error value of an image with the size $M \times N$.

A. Applying to the conventional 8-subfield system

The conventional inverse gamma correction method and the two proposed methods were applied to the conventional 8-subfiled system to visually verify their performance. In the experiments, the three methods were simulated using the gradation image. Then, the improvement of the linearity of the perceived luminance was verified by modeling the gray-scale change with respect to the horizontal direction of the result image.

As shown in Fig. 6, the step size of gradation of the proposed methods is narrower than that of the conventional one. Especially, the step size of gradation of the proposed gray-level linearization technique in the dark end of gradation image in Fig. 6(c) is about a half of that of the conventional inverse gamma correction method with $\gamma = 2.2$ in Fig. 6(a).

Considering human visual perception, the result image can be transformed to the response curve in Fig. 7. Against to the


(a)

(b)

(c)

Fig. 6. Result gradation image in 8-subfield system using (a) conventional inverse gamma correction method with $\gamma = 2.2$, (b) modified inverse gamma correction method with hybrid of $\gamma = 1.8$ and $\gamma = 2.2$, and (c) proposed gray-level linearization technique

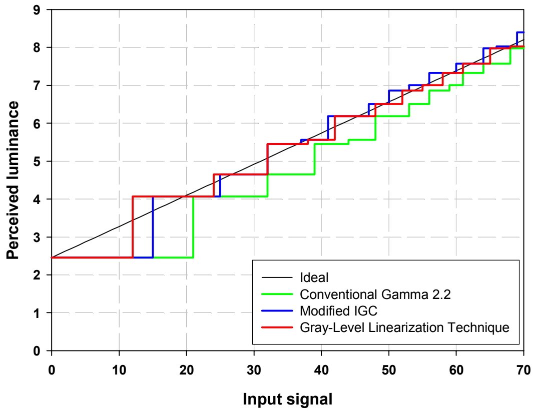


Fig. 7. Perceived luminance response curves to input signal in 8-subfield system considering human visual perception

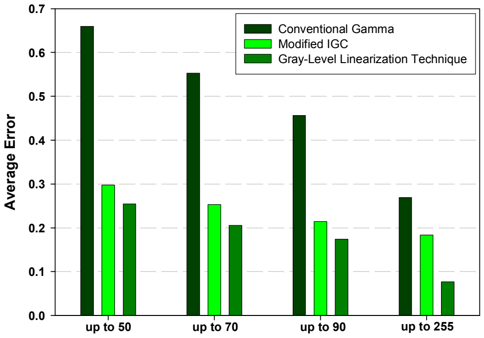
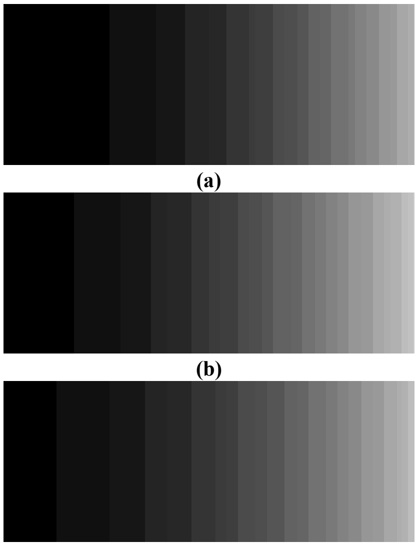


Fig. 8. Comparison of average error values in 8-subfield system

conventional inverse gamma correction method, the proposed methods not only show the linear characteristics by being located closer to the ideal response curve, but also reduce the number of merged signals into a fixed output level. As shown in Fig. 7, 20 signals in the dark end of range merged into a fixed perceived luminance of 2.455. However, the number of merged signals of the proposed gray-level linearization technique is 11, which is about a half of the that of the conventional method. In Fig. 8, the average error is tested on gradation image, which is generated with intervals of gray-levels ranging from 0 to 50, 70, 90, and 255, respectively. The results for the error measure of Eq. (13), as shown in Fig. 8, confirmed a significant decrease in the average error when using the proposed methods compared to the conventional inverse gamma correction.

B. Applying to the 9-subfield system

Similar experiments were repeated against to the 9-subfield system proposed in [5], which can reduce the number of merged input signals considerably, and reduce further nonlinearity of low gray-levels.


(a)

(b)

(c)

Fig. 9. Result gradation image in 9-subfield system using (a) conventional inverse gamma correction method with $\gamma = 2.2$, (b) modified inverse gamma correction method with hybrid of $\gamma = 1.8$ and $\gamma = 2.2$, and (c) proposed gray-level linearization technique

Similarly, the step size of gradation of the proposed methods is narrower than that of the conventional one as is shown in Fig. 9. In the dark end of gradation image, the step size of gradation of the proposed gray-level linearization technique in Fig. 9(c) is also about a half of that of the conventional inverse gamma correction method in Fig. 9(a).

In Fig. 10, the proposed methods perform better as expected. The number of merged signals is 17 at the lowest part of the luminance level for the conventional inverse gamma case, 11 for the modified inverse gamma correction, and 8 for the gray-level linearization technique. Figure 11 shows that the average errors are significantly reduced for the two proposed methods, when compared to the conventional inverse gamma correction.

As expected, the gradation images are better for the 9-subfield system than the 8-subfield (Figs. 6 and 9). The perceived luminance response curves of the 9-subfield system also follow the ideal curve more faithfully than the 8-subfield system.

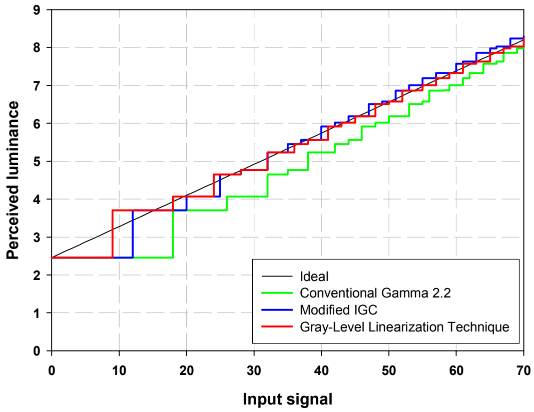


Fig. 10. Perceived luminance response curves to input signal in 9-subfield system considering human visual perception

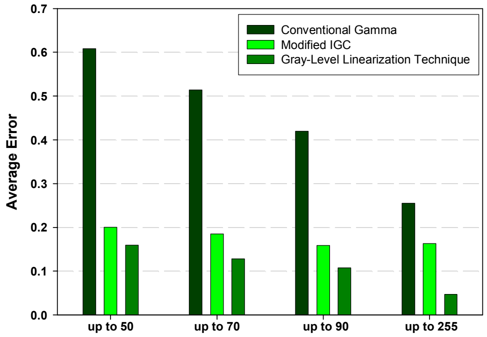


Fig. 11 Comparison of average error values in 9-subfield system

V. CONCLUSIONS

This research proposed two methods, the modified inverse gamma correction and the gray-level linearization technique, in order to improve the gray-level linearity at low gray-levels by considering the light emission characteristics of PDP and human visual perception. In the experiments, the performance of the proposed methods has been verified in terms of the response curve showing the perceived luminance with respect to an input signal and an error measure quantifying the discrepancy of the perceived luminance between the PDP and the ideal display. A series of simulations demonstrate that the two proposed methods successfully improve the linearity of the perceived luminance with respect to an input signal, especially at low gray-levels, by reducing the number of merged signals into a fixed output luminance-level. As a result, improvement in image quality has been achieved by considerably enhancing linearity of the overall gray-level.

References

[1] C. Poynton, Digital Video and HDTV: Algorithms and Interfaces, Morgan Kaufmann Publishers, 2003, pp. 257-280.
[2] L. F. Webber, "The promise of plasma displays for HDTV," in Proc. of Society for Information Display, pp. 402-405, Kobe, Japan, May 2000.
[3] S.-H. Park, C.-W. Kim, " A dithering based technique for reducing false contours in dark Areas on plasma display panel," IMID'01 Digest, pp. 468-471, 2001.
[4] K.-D. Cho, H.-S. Tae, and S.-I. Chien, "Improvement of low gray scale linearity using multi-luminance-level subfield method in plasma display panel," IEEE Trans. Consumer Electron., vol. 48, no. 3, pp. 377-381, Aug. 2002.
[5] S.-J. Kang, H.-C. Do, J.-H. Shin, S.-I. Chien, and H.-S. Tae, "Reduction of low gray-level contours using error diffusion based on emission characteristics of PDP," IEEE Trans. Consumer Electron., vol. 50, no. 2, pp. 401-406, May 2004.
[6] M. Yamada, M. Ishii, T. Shiga, and S. Mikoshiba, "A gray scale expression technique having constant increments of perceived luminance using a contiguous subfield scheme," SID 02 Digest, pp. 940-943, 2002.
[7] J.C. Stevens and S.S. Stevens, "Brightness function: effects of adaptation," Opt. Soc. Am., vol. 53, no. 3, pp. 375-385, 1963.
[8] G. Berbecel, Digital Image Display: Algorithms and Implementation, Wiley, 2003, pp. 163-181.

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