LED PWM Dimming Linearity Investigation

L. Svilainis
Signal Processing Department, Kaunas University of Technology,
Studentu str. 50, LT-51368 Kaunas, Lithuania,
phone +370 37 300532; fax. +370-37-352998; e-mail: sivilnis@ktu.lt

Abstract

LED PWM dimming application for large scale LED video displays is analyzed. The need for short light pulse duration is outlined. PWM dimming with short driving pulses is investigated experimentally. The LED response time skew introduces the nonlinearity for PWM dimming. For LED response time skew estimation, a method is suggested that has been successfully applied to measure some of today’s market representative LEDs. PWM dimming nonlinearity can be forecasted using the estimated skew. For a particular driving configuration, it is indicated that LED PWM dimming fails to satisfy the required 14 bit output coding together with the image refresh frequency of 400 Hz. A rough investigation demonstrates that the skew is quite stable. Therefore, the nonlinearity correction for the PWM pulse durations shorter than the skew value should be possible.

Keywords
LED dimming, PWM linearity, LED response time

1. Introduction

Light Emitting Diode (LED) is about to hit its 50 years anniversary. Due to increasing efficiency of LEDs compared to incandescent and even luminescent lamps, more and more often they are accepted as a light source for many applications. This technology also presents an option for information display on a flat screen offering a wide viewing angle and a bright, clear image suitable for outdoor application [1]. On large scale LED video displays, LED application imposes certain requirements for screen pixel gray scale creation.

The ease of dimming by PWM makes it attractive for large scale LED video screens. This type of control can be readily implemented in a digital form. Thanks to inexpensive and stable frequency sources, a steady driving over a wide range of intensities can be ensured. But is the LED response stable?

The aim of this paper is to analyze the LED PWM dimming application on LED video displays outlining the need for short driving pulse durations and investigating the dimming linearity and stability.

2. Need for a Short Driving Pulse

LED luminance can be controlled by the diode forward current [2]. Modern LED video screens are demanded to be in color. But the forward current affects the LED emission wavelength. If LED could be operated at a constant current, this would ensure the screen color gamut stability. The most convenient method for LED dimming without altering the current is the pulse-width-modulation (PWM) [3]. Average power, thereby the expected light output, of PWM should be linearly proportional to pulse duration:

\[ Y = Y_n \frac{t_{on}}{T}, \quad (1) \]
here $T$ is PWM period, $Y_n$ is the maximum luminance (100% duty), $\tau_{on}$ is PWM pulse duration when LED is on and $Y$ is the resulting luminance. PWM period usually is divided into $2^N$ levels (discrete time intervals). Then $N$ bits are required to code the pixel intensity with PWM. Then time step interval $\tau_{\text{min}}$ is the following:

$$\tau_{\text{min}} = \frac{T}{2^N}, \quad (2)$$

The smallest reachable time interval $\tau_{\text{min}}$ defines the lowest PWM dimming intensity attained.

The nonlinearity of the human sense of light [4] requires specific approach to light coding. The image camera capturing mimics the human visual system. This nonlinearly coded (gamma-corrected) signal is transformed back to linear intensity at the display (inverse gamma), using a nonlinear voltage-to-intensity response inherent for the CRT. Coding the video image intensity into a gamma-corrected signal makes the maximum perceptual use of the channel. When an image has to be displayed on the linear response display (the LED video screen driven with PWM), an inverse gamma correction is a must. The imaging system requires an inverse gamma correction to mimic the nonlinear CRT display response. This means that the higher number of LED brightness levels is needed for output since some of the codes shall be thrown away for the sake of linearization in human perception. Mathematically, the conventional 24 bit coded pixel color 8 bit input code $C_{\text{in}}$ conversion to the gamma-corrected (CRT mimicking) code $C_{\text{Gamma}}$ with resolution of $N$ bits can be expressed as follows:

$$C_{\text{Gamma}} = \text{round}\left(\frac{C_{\text{in}}}{255}\right)^\gamma\left(2^N - 1\right). \quad (3)$$

Such gamma correction will exhibit some rounding approximation error:

$$\delta_{\text{approx}} = \frac{C_{\text{Gamma}} - \frac{C_{\text{in}}}{255}\gamma\left(2^N - 1\right)}{\left(\frac{C_{\text{in}}}{255}\gamma\left(2^N - 1\right)\right) - 1} \cdot 100\%.$$  

For example, when applying a 2.4 gamma correction only a code using 19 bit resolution is capable of monotonic variance – every change in an input code (8 bits) causes change in an output code within the same direction. An approximation error will be large at the lower end of the coding table – this is clearly demonstrated by an error graph for 10 bit output coding presented in Fig. 1.
Aproximation error, $\delta_{\text{aprox}}$(%)

Analysis of this error is summarized in Table 1. The table lists the percentage of codes at the lower end of the coding table that fail to meet the specified approximation error.

![Fig. 1. Gamma correction approximation error for 10 bit output coding](image)

**Table 1**

<table>
<thead>
<tr>
<th>Error $\delta_{\text{aprox}}$ limit, %</th>
<th>8bit</th>
<th>10bit</th>
<th>12bit</th>
<th>14bit</th>
<th>16bit</th>
<th>19bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>18</td>
<td>12</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>14</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>37</td>
<td>20</td>
<td>12</td>
<td>6</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>48</td>
<td>27</td>
<td>16</td>
<td>10</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

In which way Table 1 should be interpreted? Table data should be compared against other intensity variation sources. Variation in the LED peak intensity below 5% is impossible to be achieved. In addition, a LED driver is already distorting the expected luminance level – driving current mismatch can reach maximum 6%. Therefore, it makes no sense in reaching the gamma correction curve match better than that. This will correspond to 5% row in Table 1. Which $C_{\text{Gamma}}$ code length shall be used then? The lowest intensity levels are insignificant, as important image information is not stored at extremely low intensity. Sometimes, analog video uses 7.5% offset [4]; studio digital video can use black at 6.2% [4]; ITU recommendation 709 uses a linear slope below the level 8.1% [5]. Therefore, due to this analysis we may conclude that the loss in coding accuracy at 7% of the lower part of the coding table is acceptable. Then the code length above 12 bit is desirable. It should be noted that if a LED driver allows for individual LED current adjustment (dot correction), it makes sense to revise the considerations presented above.

Flicker occurs when changes in the display luminance occur at the frequency below the integrating capability of an eye. The 100 Hz frequency is usually assumed as sufficient to avoid flicker. For professional LED screen application, camera shooting speed defines the LED screen image refresh frequency. Usually, 400 Hz refresh frequency is used. Some claim success at 240 Hz [6], while other LED screen manufacturers indicate that 1000 Hz frequency is required to completely get rid of the problem. Refresh frequency $f_{\text{refr}}$ and the number of
PWM levels define the minimum duration of $\tau_{on}$. Data in Table 2 lists the required duration $\tau_{min}$ relation to code length.

Table 2
Required minimal pulse duration versus PWM code length

<table>
<thead>
<tr>
<th>Bits</th>
<th>Required $\tau_{min}$, ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>39063 16276 7813 3906</td>
</tr>
<tr>
<td>10</td>
<td>9766 4069 1953 977</td>
</tr>
<tr>
<td>12</td>
<td>2441 1017 488 244</td>
</tr>
<tr>
<td>14</td>
<td>610 254 122 61</td>
</tr>
<tr>
<td>16</td>
<td>153 64 31 15</td>
</tr>
<tr>
<td>19</td>
<td>19 8 4 2</td>
</tr>
</tbody>
</table>

According to the data in Table 2, demand for LED response speed increases rapidly if high refresh frequency and wide output coding are required. Keeping in mind the analysis of Table 1 results and data of Table 2, for the most common 400Hz refresh one will see that the required minimal achievable pulse duration should be about 150ns. Therefore, it was decided to investigate whether such fast LED switching is possible or not, and what linearity can be expected at such short durations.

3. PWM Performance Study

Two factors limiting the shortest PWM pulse duration are the following: driver response time and LED response time. Usually, driver response time is clearly stated by a manufacturer. LED manufacturers generally are not aware of the need for faster LED response times. Normally, it is considered to be fast enough to satisfy dimming requirements. LED manufacturers do not specify the response time. Literature [7-10] analysis revealed that LED speed could get several ns to hundreds of ns. LED transient response depends on the LED chip structure, doping level, technology applied and driving conditions. Therefore, investigation was needed to evaluate the current state of the response time of visible light LEDs.

3.1. LED Response Time Influence on PWM Linearity

LED electroluminescence (electrooptical) response is obtained by measuring the light output temporal response relative to the current of a driving signal. In the paper [7], LEDs were driven with a conventional fast-rise pulse generator ($t_R < 1$ ns). For light impulse detection, Hamamatsu R406 photomultiplier was used. A photomultiplier signal was fed to the sampling scope. The light-delay time was determined by measuring the time interval between the 50% point of the leading edge of an excitation current pulse and the 2% point of the light-intensity rise. Such technology, however, is rather complicated and expensive, therefore, a less expensive measurement method was required.

LED response time will influence the LED intensity obtainable with PWM. It could be assumed that if LED response speed for turn-on (specified by time $t_R$) and turn-off ($t_F$) process is asymmetrical, this will introduce the nonlinearity for LED PWM dimming. Measuring this nonlinearity, LED response time can be estimated. In order to check this idea, a simple LED response $Y(t)$ model [2] employing an asymmetric exponential rise and fall response was applied. Using an integrating photosensor, the average radiance can be registered. Assuming a
monochromatic LED emission, this can be assigned to an average luminance. Fig. 2 may be referred to for the most informative modeling results. Pulse repetition period $T$ was 400 ns. Various $t_R$ and $t_F$ time combinations were evaluated. The light pulse energy is calculated by integrating the electrooptical response $Y(t)$ over the PWM period. The ideal light pulse energy is assumed to be equal to the full-scale light output value $Y_n$ multiplied by duty $\tau_{on}/T$. The nonlinearity error is a difference of the two, normalized by full-scale light output value $Y_n$ and expressed in percents:

$$\delta_{skewed}(\tau_{on}) = \frac{\int_0^T Y(t)dt - Y_n \tau_{on}}{Y_n} \cdot 100\%.$$  

This is the expression of average luminance supposed to be sensed by a human eye or averaging photosensor (radiance).

![Diagram showing modeled nonlinearity error for PWM as a pulse asymmetry result](image)

Fig. 2. Modeled nonlinearity error for PWM as a pulse asymmetry result

As Fig. 2 demonstrated, a full-scale normalized nonlinearity error is in direct proportion of the time skew. For instance, with $t_R=120$ ns, $t_F=40$ ns, time skew is 80 ns, which is 20% of 400 ns full-scale value. However, the maximum nonlinearity error seen in Fig. 2 is twice lower, i.e 10%. The same result is for $t_R=50$ ns, $t_F=10$ ns and $t_R=41$ ns, $t_F=1$ ns. This relation can be easier arrived at using a simplified response model (refer to the drawing at Fig. 3). The transient response exponent is replaced by linear approximation. Actually, the area $S$ under the curve is the light pulse energy, if some proportion of radiance to radiometric flux can be established.
The resulting light pulse energy is expressed using geometry in Fig. 3:

$$E_{\text{skewed}} = \frac{Y_n t_R}{2} + Y_n(t_{\text{on}} - t_R) + \frac{Y_n t_F}{2} = Y_n t_{\text{on}} + Y_n \left(\frac{t_F - t_R}{2}\right).$$

Full-scale light pulse energy can be the following:

$$E_{\text{max}} = Y_n T.$$  

Equation (1) divided by $T$ can be used for ideal pulse energy estimation. Then a full-scale normalized error of such a skewed pulse is as follows:

$$\delta_{\text{skewed}}(t_{\text{on}}) = \frac{\frac{Y_n t_{\text{on}}}{2} + \frac{Y_n (t_F - t_R)}{2} - Y_n t_{\text{on}}}{Y_n T} \cdot 100\% = \frac{t_F - t_R}{2T} \cdot 100\%.$$  

Solution for the time skew:

$$t_F - t_R = \Delta t = \frac{2T \cdot \delta_{\text{skewed}}}{100\%}.$$  

Equation (9) will be used for skew time estimation.

3.2. Measurement

Referring to this theoretical simplification, the real LEDs measurements have been carried out. For measurements speed and automation, a measurement system has been developed. A system diagram is presented in Fig. 4. A light-to-frequency converter TCS230 from Texas Advanced Optoelectronic Solutions Inc. [11] has been chosen as an averaging photosensor. A sensor converts irradiance to frequency, linearity at low irradiance is 1%. All control operations and data collection are accomplished via USB interface by host PC. 16bit current output DAC AD420 from Analog Devices, Inc. [12] is used as a current source. It provides 0.002% typical integral nonlinearity. Turn-on time will be defined by constant current source interaction with LED. In order to turn-off LED promptly, its terminals are short-circuited by N-Channel MOSFET [13]. This enhancement mode DMOS technology field effect transistor has been chosen for good combination of gate charge (e.g. switching speed) and on-state resistance (good LED tampering). Driven by a fast low output impedance PWM driver, such MOSFET is expected to switch within a couple of nanoseconds. A fast gate driver has been used, therefore its speed influence on results is minimized. The sensor output frequency meter integration period is much longer than PWM period, therefore the number of averaged PWM periods makes no influence on the measurement result.
For initial investigation, PWM linearity was tested with 32 steps PWM at repetition frequency of 2.5 MHz. This results in 400 ns PWM period and a 12.5 ns shortest PWM duration. A full-scale normalized nonlinearity error (calculated applying equation (5)) versus pulse duration for three different color LEDs is plotted in Fig.5.

Application results of equation (9) and 400 ns period (1/2.5 MHz) for the skew time are presented on the labels of Fig. 5. Variation of results between different color LEDs is about 2%. As measurement duration was very short, there was no visible variation in the middle of the duty range. Experiments have been repeated with 125 kHz 32 steps PWM (refer to Fig.6). Various frequency meter integration periods have been used.
The results are applied for the same LED. Note the different response that was influenced by different measuring speed conditions. This can be explained by normalizing conditions. For calculation of the skew induced nonlinearity error in equation (5), the values obtained are normalized by 100% duty intensity $Y_n$. The LED light output performance is strongly dependant on temperature. The LED chip temperature rises due to electrical power consumed by LED and then stabilizes at a temperature value when a thermal equilibrium is reached in the chip after a period of time [14]. Due to this effect, the emitted light is not stabilized as far as this equilibrium is reached. The stabilization procedure can last several seconds or up to a minute. This is clearly seen in Fig. 6 – data for 10 s and 100 s is almost the same. As 32 data points are measured, this corresponds to 5 min and 50 min respectively. At low duty ratios, LED chip does not generate too much heat, so the obtained response does not differ much. At high duty ratios, the relative intensity is high enough not to be influenced by unstable 100% duty intensity $Y_n$ used for normalization. As Fig. 6 demonstrates, the nonlinearity error value variation is the greatest at 50% duty. Inspection has been carried out to investigate how this value will vary over time if normalization value $Y_n$ is obtained after every measurement. This algorithm was chosen to eliminate the influence of LED preheat time. For LED video screen application, preheat should not be the case – LEDs are potted in a silicon compound with good heat conductivity, therefore after some time temperature of the junction will stabilize to some average value and fluctuation will be much slower. In order to simulate such an operation mode, LED measurement at 50% duty cycle was followed by 100% duty. The 100% duty was kept for a longer time period. This 100% duty intensity was used to normalize the value obtained at a current duty ratio. Measurements took 10 min. LEDs of the three main color have been investigated: green (527 nm, InGaN), blue (467 nm, InGaN) and red (628 nm, AlGaInP). Despite of some trend in $Y_n$, similar trend was noted on $Y$. Therefore, the time skew results indicate only negligible trend during the first 3 min period. Standard deviation $\sigma_{\Delta t}$ for the time skew was calculated for every LED. Results are summarized in Table 3.

<table>
<thead>
<tr>
<th>LED</th>
<th>$\Delta t$, ns</th>
<th>$\sigma_{\Delta t}$, ns</th>
<th>Trend, ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>75.4</td>
<td>0.44</td>
<td>9.4</td>
</tr>
</tbody>
</table>
It should be noted that experiments indicate the stability of the error introduced by the skew. The next series of experiments carried out were using different LEDs from the same manufacturing lot. The results for blue LED are presented in Fig. 7. In order to reduce preheat influence, same compensation was used. At every duty cycle, LED measurement was followed by 100% duty for normalization purposes. Note how flat the response (Fig. 7) is now. In order to check for PWM duty change directionality influence (increasing or decreasing duty), an experiment has been carried out with increasing pulse duration (dashed line) and decreasing pulse duration (dotted line). No distinct difference between these two responses was observed.

Fig. 7. Calculated skew time within one manufacturing lot for blue LED

In order to investigate how the experiment results for the skew time were distributed among three colors, Fig. 8 was generated. This figure indicates the count frequency for skew time $\Delta t$. The skew time was measured in the middle range of the duty cycle (400 ns to 1200 ns, refer to Fig. 7).
Fig. 8. Skew time count frequency distribution for the main LED colors.

It can be clearly seen that red color (AlGaInP) skew time $\Delta t$ has smaller deviation. The averaging for one manufacturing lot has been performed in order to obtain some evaluation. The obtained results are summarized in Table 4. The time skew average is noted as $\bar{\Delta t}$, whereas standard deviation as $\sigma_{\Delta t}$.

Table 4

<table>
<thead>
<tr>
<th>LED</th>
<th>$\Delta t$, ns</th>
<th>$\sigma_{\Delta t}$, ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>74.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Green</td>
<td>91.7</td>
<td>8.7</td>
</tr>
<tr>
<td>Blue</td>
<td>86.2</td>
<td>7.6</td>
</tr>
</tbody>
</table>

4. Results Application

Usage of the estimated time skew value allows calculating PWM performance of any period. Nonlinearity $\delta_{\text{nonl}}$ due to light pulse skew can be calculated as a measured average intensity $Y_{\text{meas}}$ error from expected intensity predicted by a current duty ratio, normalized by expected intensity:

$$
\delta_{\text{nonl}}(\tau_{\text{on}}) = \frac{Y_{\text{meas}} - Y_n \frac{\tau_{\text{on}}}{T}}{Y_n \frac{\tau_{\text{on}}}{T}} \cdot 100 \% .
$$

(10)
Assuming that $Y_{\text{meas}}$ value can be obtained dividing equation (6) by period $T$, nonlinearity is the following:

$$
\delta_{\text{nonl}}(\tau_{\text{on}}) = \frac{I_E - I_R}{2\tau_{\text{on}}} \cdot 100\% = \frac{\Delta t}{2\tau_{\text{on}}} \cdot 100\% . \tag{11}
$$

The measured blue LED PWM nonlinearity results obtained at various refresh frequencies can be combined into one graph and compared against the calculated value obtained using (11) and skew in Table 3. For the intensity nonlinearity error normalized by expected intensity, refer to the Fig. 9.

![Graph showing the relationship between pulse duration and relative error](image)

Fig.9. Intensity normalized nonlinearity PWM error

Table 2 lists the PWM pulse duration required versus output coding bits number. Now, Table 2 can be modified taking into account the 100 ns skew as the worst case of the results in Table 4. By solving equation (12) for PWM pulse duration $\tau_{\text{on}}$, it is possible to obtain the achievable PWM code width in bits. Calculated values for various refresh times are presented in Table 5.

<table>
<thead>
<tr>
<th>Refresh, Hz</th>
<th>100</th>
<th>240</th>
<th>500</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{\text{skew}}, %$</td>
<td>Bits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>15</td>
<td>14</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>14</td>
<td>13</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>12</td>
<td>11</td>
<td>10</td>
</tr>
</tbody>
</table>

Results of Table 5 indicate that the LED response time skew is introducing a serious limitation for the PWM dimming linearity, thus for the obtainable image coding. Therefore, it appears that the LED response is a limiting factor for PWM dimming width.

One might end up by the idea that nonlinearity can be compensated. The analysis results in Table 3 and Table 4 indicate that such approach is feasible. The time skew is quite stable
both in time and within a manufacturing lot. Compensation can be carried out in the two following ways.

The simplest solution is to use driving pulse skew pre-compensation. For widening of analyzed LEDs, every PWM duty cycle by 100 ns will allow reducing nonlinearity, thus the number of available codes, almost for 10 times. Certainly, this will reduce the code availability at PWM cycle edges – close to 100% and close to 0%.

Applying a more complicated solution, the calibrated LED response may be used for codes selection. In this case, the codes may be applied more efficiently. However, usually more complicated PWM modulation algorithms are used [3, 15]. Such PWM modulation nonlinearity will have more complex response, therefore it should be studied for the artifacts indicated in this paper.

5. Conclusions

A simple method for LED response time skew estimation was suggested. Using the estimated skew, PWM dimming nonlinearity may be forecasted for various refresh frequency and code length combinations. It has been estimated, that the LED response time features the skew of approximately 100ns. This fact introduces nonlinearity for PWM dimming, when applied for LED video applications.

It has been indicated that 14 bits coding is a reasonable coding length, if 5% variation in image intensity is acceptable. An investigation, however, indicates that 14 bit PWM dimming is achievable only at refresh rates below 100 Hz. At desired refresh of 400 Hz, PWM dimming linearity within 5% is satisfied only by 11 bits code. This means that approximately 10% of input codes are above 5% accuracy if 2.4 gamma correction is used.

An experimental investigation demonstrates that the LED response time skew induced error is sufficiently stable and should allow the nonlinearity correction in order to apply the PWM pulse durations shorter than the indicated skew. In this case, code length can be increased. However, in order to evaluate this correction performance, a further study is needed.

Acknowledgement

The author would like to thank Dr V.Dumbrava for a range of helpful discussions and critical notes.

References


Figure Legends

Tables