

Displaying gray shades in liquid crystal displays

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Abstract. Quality of image in a display depends on the contrast, colour, resolution and the number of gray shades. A large number of gray shades is necessary to display images without any contour lines. These contours are due to limited number of gray shades in the display causing abrupt changes in grayness of the image, while the original image has a gradual change in brightness. Amplitude modulation has the capability to display a large number of gray shades with minimum number of time intervals [1,2]. This paper will cover the underlying principle of amplitude modulation, some variants and its extension to multi-line addressing. Other techniques for displaying gray shades in passive matrix displays are reviewed for the sake of comparison.

Keywords. Liquid crystal displays; addressing; multiplexing; gray shades.

PACS No. 85.60.P

1. Introduction

Liquid crystal displays (LCDs) are thin and can be fabricated in almost any size and format. They consume less power as compared to other display devices and operate with low voltages. Hence, LCDs have an advantage over other types of displays for use in portable products. LCDs are broadly classified as passive matrix and active matrix. Passive matrix displays exploit the intrinsic non-linear electro-optic characteristics for matrix addressing or multiplexing. They are mostly used in applications like personal digital assistant (PDA), mobile phone and other low to moderate information content applications wherein power consumption should be as low as possible. Active matrix LCDs have a thin film transistor incorporated with each pixel. These transistors act as a switch to charge and hold the desired voltage across a pixel. Passive matrix LCDs are easy to fabricate and cost less as compared to the active matrix LCDs. Current trend demands gray scale and colour capabilities even for the displays in mobile phones. Passive matrix LCDs will be preferred as long as the cost and power consumption are low as compared to the active matrix LCDs. Hence it is important that the gray shade techniques used in passive matrix displays should not increase the hardware complexity or cost of the drive electronics. The number of gray shades is an important criterion in the choice of a technique for displaying gray shades. Figure 1 shows the images of an egg with varying number of gray shades. The shape of the egg itself is lost in figure 1a, because edge in the darker region of the egg cannot be distinguished from the background, since the gray shade in that region is the same as that of the background. We can also see the contour lines and false gradients in some images

when the number of gray shades is small as in figure 1b–1d. At least 64 gray shades (6 bits) are necessary to display this image realistically with gradual change in brightness and to eliminate contour lines due to abrupt changes in gray shades. These contours can also be seen in figure 2 when the number of gray shades is less than 32 (5 bits). Hence, at least 32 to 64 gray shades are necessary to reproduce the images to an acceptable quality. Amplitude modulation can be used to display a large number of gray shades in passive matrix displays.

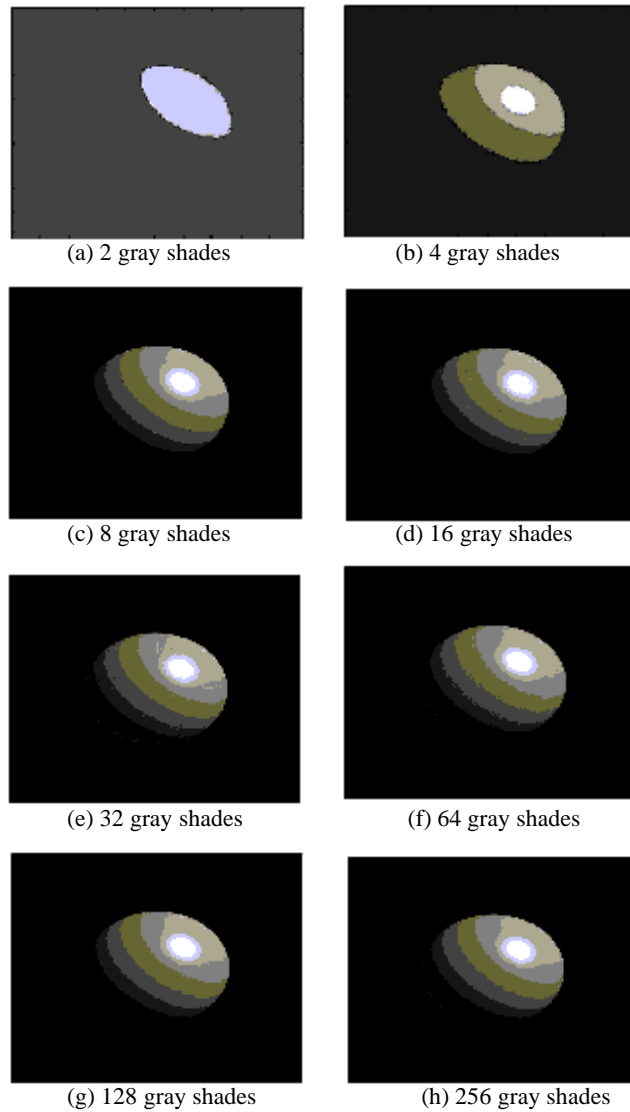


Figure 1(a)–(h). Image of an egg with varying number of gray shades.



Figure 2(a)–(f). Image of Lena with varying number of gray shades.

2. Background

A brief introduction to line-by-line addressing technique for driving matrix LCDs and several gray scale techniques apart from amplitude modulation are briefly outlined in the following sections as background information. The review starts with a brief introduction to conventional line-by-line addressing for displaying binary images.

2.1 Line-by-line addressing

Conventional line-by-line addressing [3,4] is based on selecting the rows of a matrix display one at a time. This technique is for displaying binary images with pixels driven to either ON or OFF state. A row is selected in line-by-line addressing with a pulse of amplitude $+V_r$, while the remaining $(N - 1)$ rows are grounded. Voltages applied to the column correspond to the state of the pixels in the selected row. Column voltages are $+V_c$ for OFF pixels and $-V_c$ for ON pixels. It is important to note that column voltages have same amplitude (V_c) and just the polarity of these voltages is determined by the state of the pixels

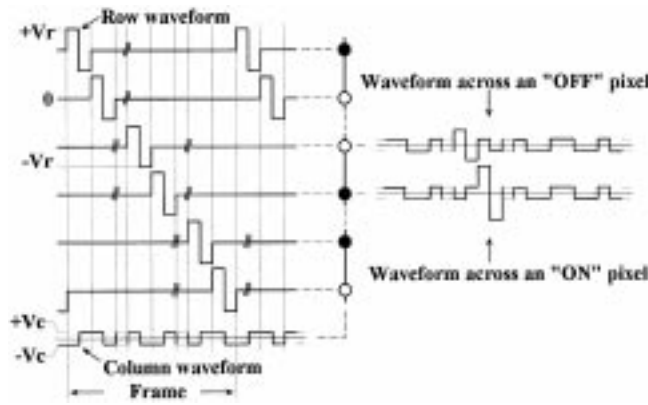


Figure 3. Line-by-line addressing.

in the selected row. Both the row and column voltages are applied simultaneously for the time duration τ . A frame is complete when all the rows are selected once. The life of liquid crystal displays is reduced if a DC voltage is present across the pixels for a long duration of time. Hence the polarity of both row and column voltages are reversed in a periodic manner to achieve a DC-free operation. Figure 3 shows the typical row and column waveforms of line-by-line addressing. Polarity reversal is incorporated within a row select time in these waveforms. The display is refreshed continuously by scanning it repeatedly with a frame frequency high enough to suppress flicker. The following expression gives the rms voltage across a pixel in a display driven by line-by-line addressing

$$V_{\text{rms}} = \sqrt{\frac{(V_r - d_{ij}V_c)^2 + (N - 1)V_c^2}{N}} = \sqrt{\frac{V_r^2 - 2d_{ij}V_rV_c + NV_c^2}{N}} \quad (1)$$

Data d_{ij} in the above expression represent the state of a pixel in row i and column j and it is assigned a value $+1$ for an OFF state and -1 for an ON state. Selection ratio is defined as the ratio of rms voltage across ON pixel to that of OFF pixel.

$$\text{Selection ratio} = \frac{V_{\text{ON}}}{V_{\text{OFF}}} = \sqrt{\frac{V_r^2 + 2V_rV_c + NV_c^2}{V_r^2 - 2V_rV_c + NV_c^2}} \quad (2)$$

This ratio is a measure of discrimination between the ON and OFF pixels and a high value is preferred to achieve good contrast in the display. The rms voltage across OFF pixels is also maintained to be just below the threshold voltage to ensure a high contrast in the display. The selection ratio is maximum when $(V_r/V_c) = \sqrt{N}$.

$$\text{The maximum selection ratio} = \sqrt{\frac{\sqrt{N} + 1}{\sqrt{N} - 1}} \quad (3)$$

This is also the maximum achievable by any addressing technique while driving passive matrix LCD. Line-by-line addressing is analogous to time division multiplexing in communication. In fact, addressing matrix LCDs is also called multiplexing. Information to be

displayed in a column is multiplexed through the column address line, while the rows are selected sequentially one after the other. The row waveforms are derived from orthogonal functions and they correspond to the carriers. A unit matrix of order N is the orthogonal matrix for the line-by-line addressing and the row select pulses in the row waveforms correspond to the diagonal elements of a unit matrix. Column waveforms are derived from orthogonal transform of the data to be displayed in the corresponding columns and they correspond to the multiplexed signals. Column voltages in line-by-line addressing are proportional to the data itself, because multiplication by unit matrix does not alter the data. In fact the middle term $2V_rV_c$ in eq. (1) corresponds to multiplication of carrier and multiplexed signal in a demultiplexer. Slow response of liquid crystal displays provides the integration necessary for demultiplexing. First and last terms (V_r^2 and NV_c^2) in this equation correspond to energies in the row and column waveforms and when these two terms are constant, the sign of the middle term decides the state of a pixel. Choosing the amplitude of the column voltages to be the same for both states of the pixels ensures that the last term is a constant. Hence, the rms voltage across pixels is independent of the data being displayed in that column (elimination of cross talk between the channels). The rms voltage across a pixel will depend on the actual number of ON and OFF pixels in that column in case amplitude of column voltage is different for the two states. Amplitude modulation has an interesting way of surmounting this problem (see §3). Line-by-line addressing has three voltage levels in row waveforms and two voltage levels in column waveforms. Hardware complexity of drivers is an important factor in the cost of a display because each row or column in the display needs a driver. Any reduction in hardware complexity of a driver has a multiplying effect since the number of rows and columns is usually large in a matrix display. Techniques for displaying gray shades will be evaluated on the basis of hardware complexity because cost is an important consideration in passive matrix LCDs. Frame modulation, a common method used for displaying gray shades in passive matrix LCDs is outlined in the next section.

2.2 Frame modulation

Frame modulation is also known as frame rate control [5]. Here, the pixels are either turned ON or OFF in successive frames. These pixels appear gray, depending upon the number of times a pixel is switched ON during a cycle consisting of several frames. While switching pixels between ON and OFF states would appear as flicker in fast responding displays, a gray shade is perceived in LCDs due to their slow response and persistence of vision. The rms voltage across a pixel when f consecutive frames are used to display $(f + 1)$ gray shades is

$$\begin{aligned}
 V_{\text{rms}} &= \sqrt{\frac{\sum_{k=1}^f [(V_r - d_{ijk}V_c)^2 + (N-1) \cdot V_c^2]}{N \cdot f}} \\
 &= \sqrt{\frac{f \cdot V_r^2 - 2V_rV_c \sum_{k=1}^f d_{ijk} + f \cdot N \cdot V_c^2}{N \cdot f}}, \tag{4}
 \end{aligned}$$

where d_{ijk} is the data of a pixel in the frame k of a cycle. Typical waveforms of frame modulation while displaying four gray shades are illustrated in figure 4. Flicker will be

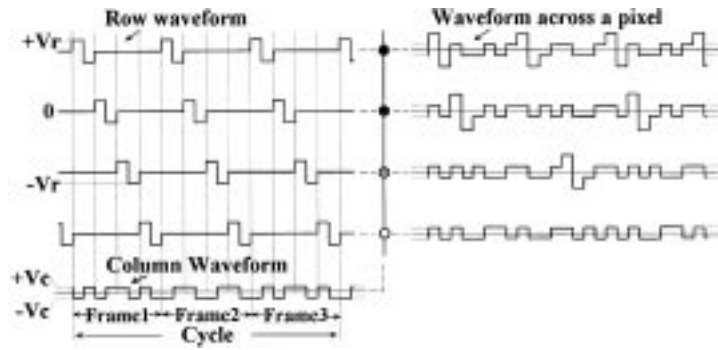


Figure 4. Frame modulation.

seen when the number of frames in a cycle is large. Hardware complexity of the drive electronics does not increase when frame modulation is used. In fact it is the same as that for displaying binary images without any gray shades, since each pixel is driven to just one of the two states in each frame. Selection ratio is also not compromised and is the same as the maximum shown in eq. (3). Frame modulation has been popular with super twisted nematic (STN) LCDs. STN LCDs have response times in the range of 100–200 ms. Sixteen gray shades can easily be displayed without flicker in these displays with slow response times. Frame modulation is not suited for displays in television and other applications wherein the image changes rapidly. Pulse width modulation is a better choice in such applications to display gray shades and this method is discussed briefly in the next section.

2.3 Pulse width modulation

Column voltage of a pixel is switched between two voltages within a row select time of line-by-line addressing [6]. The two voltages are $+V_c$ and $-V_c$ corresponding to OFF and ON state in a display without gray shades. Here again $(w + 1)$ gray shades can be displayed using w time intervals in each row select time. The rms voltage across a pixel when the voltage corresponding to an ON state is applied to a column for a time duration τ during a row select time and voltage corresponding to OFF state during rest of the time interval is:

$$\begin{aligned}
 V_{\text{rms}} &= \sqrt{\frac{\tau \cdot (V_r + V_c)^2 + (1 - \tau) \cdot (V_r - V_c)^2 + (N - 1)V_c^2}{N}} \\
 &= \sqrt{\frac{V_r^2 + 2(2\tau - 1)V_r V_c + NV_c^2}{N}}. \tag{5}
 \end{aligned}$$

Typical waveforms for displaying four gray shades using pulse width modulation are illustrated in figure 5. A $(w : 1)$ analog multiplexer is used in the column driver for each output to apply any one of the w waveforms with τ ranging from 0 to 1. Duty cycle of these waveforms corresponds to the gray shade to be displayed by a pixel in the selected row. Refresh rate of the display may be increased by a factor w , to avoid increase in the

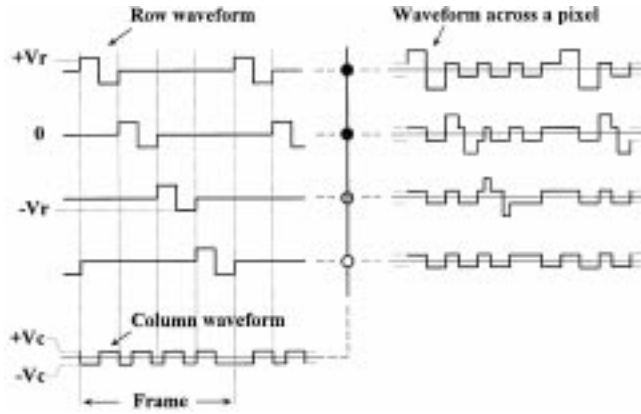


Figure 5. Pulse width modulation.

hardware complexity of the column drivers. Pulses in the column waveforms become narrower as the number of gray shades is increased. This leads to brightness nonuniformity of pixels due to RC time constant (resistance of driver and ITO electrodes along with the capacitance of the pixels) in the matrix display.

2.4 Row pulse amplitude modulation

Amplitude of the row pulses can be modulated in several frames. Although this technique [7] was proposed for multi-line addressing, it could be used in combination with any addressing technique. Row pulse amplitude modulation is explained here with reference to the line-by-line addressing. Let $2^k V_r$ be the amplitude of the row select pulse in the frame k of a cycle consisting of f frames. Amplitude of the column voltage is same (V_c) in all the frames and the sign of the column voltage is decided by one of the bits of data representing gray shade to be displayed in a pixel of a selected row. The least significant bit of the data is used for $k = 0$ and the corresponding amplitude of the row select pulse is V_r . Amplitude of row select pulse is doubled while using the next significant bit $k = 1$ in a frame. The next significant bit of the data decides sign of column voltage. Amplitude of the row select pulse is doubled for the subsequent frame using the next higher significant bit of the data. This process is repeated till one uses the most significant bit. A cycle is complete when all the bits of gray shade data are considered once and the display is refreshed with corresponding modulation in the amplitude of the row select pulse. The liquid crystal display is refreshed continuously by repeating this cycle. The rms voltage across a pixel in a display with row pulse amplitude modulation using f bits of gray shade data and frames is

$$\begin{aligned}
 V_{\text{rms}} &= \sqrt{\frac{\sum_{k=0}^{f-1} [(2^k V_r - d_{ijk} V_c)^2 + (N - 1) V_c^2]}{N \sum_{k=0}^{f-1} 1}} \\
 &= \sqrt{\frac{\frac{(4^f - 1)}{3} V_r^2 - 2 V_r V_c \sum_{k=0}^{f-1} 2^k d_{ijk} + N \cdot f \cdot V_c^2}{N \cdot f}}. \tag{6}
 \end{aligned}$$

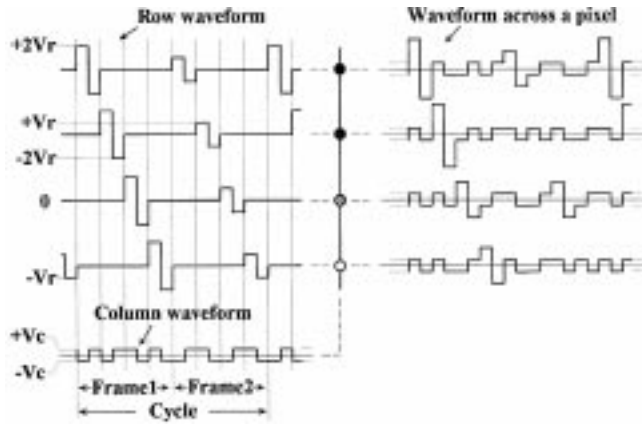


Figure 6. Row pulse amplitude modulation.

If there are f frames in a cycle then 2^f gray shades can be displayed. Selection ratio for this technique is lower than that given in eq. (3) and this is the main drawback of row pulse amplitude modulation. Supply voltage of the drive electronics is higher than the conventional technique. Number of levels in the row waveform increases as the number of gray shades is increased. Typical waveforms of row pulse amplitude modulation are shown in figure 6.

2.5 Successive approximation

The successive approximation technique is to some extent similar to the row pulse amplitude modulation. Amplitude of both row and column voltages is modulated in successive frames instead of just row voltages in the row pulse amplitude modulation technique. Let V_r and V_c be the amplitudes of row and column voltage when a matrix display is scanned with least significant bit of gray shade data. Amplitude of both row and column voltages are increased by a factor $\sqrt{2}$ while using next significant bit of the data to scan the display during successive frames. This process is continued till the display is scanned with the most significant data to complete a cycle. Display is refreshed continuously by repeating this cycle at a sufficiently fast rate to avoid flicker. Typical waveforms of successive approximation technique are shown in figure 7. The rms voltage across a pixel in row i and column j is given by

$$V_{rms} = \sqrt{\frac{\sum_{k=0}^{f-1} ((\sqrt{2})^k V_r - d_{ijk} (\sqrt{2})^k V_c)^2 + (N-1) \sum_{k=0}^{f-1} 2^k V_c^2}{\sum_{k=0}^{f-1} N}},$$

$$V_{rms} = \sqrt{\frac{(2^f - 1) \cdot (V_r^2 + N V_c^2) - 2 \sum_{k=0}^{f-1} d_{ijk} 2^k V_r V_c}{f \cdot N}}. \quad (7)$$

Here selection ratio is the maximum when $V_r = \sqrt{N} V_c$ and the maximum selection ratio is the same as that of line-by-line addressing given in eq. (3). It is important to note that in each frame the number of voltage levels in the addressing waveforms is the same as

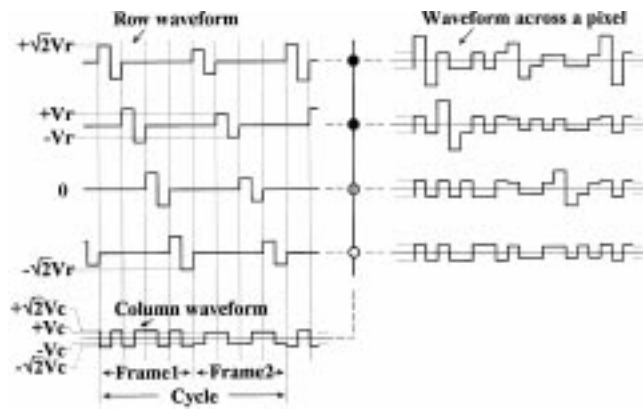


Figure 7. Successive approximation.

that of conventional technique. However, the amplitudes are different in different frames, and depend on the data bit (MSB, LSB, etc.) used for scanning the frame. In successive approximation technique both row and column drivers are the same as that used for displaying binary images without any gray shades. This is possible because change in amplitude of row and column waveforms is the same for all the rows and columns and hence common multiplexers may be used to select the voltage levels based on the data bit used for scanning a frame. Same idea could also be used to reduce hardware complexity of row drivers in the row pulse amplitude modulation technique. However, successive approximation technique achieves the maximum selection ratio while the row pulse amplitude modulation has a lower selection ratio. The principle of successive approximation can be extended to several addressing schemes. A row select time may be divided into a number of time intervals. Amplitudes of both row and column voltages may be changed depending on the bit used in each time interval. We have also demonstrated the successive approximation technique with multi-line addressing [8]. All these implementations of successive approximation retain the advantage of both the maximum selection ratio and low hardware complexity. 2^f gray shades can be displayed using f frames in a cycle. Photograph of a display addressed with successive approximation technique is shown in figure 8.

Other techniques like using sub-pixels with ratio of their areas in powers of two (1:2:4:8 etc.) increase the number of pixels in a display. The cost of the display also increases since the number of drivers will be more. In some cases the number of lines being multiplexed may also increase, leading to a reduced contrast of the display. Hence this approach is not popular for displaying gray shades in passive matrix LCDs except in ferro-electric LCDs, wherein the contrast can be independent of rows being multiplexed. Amplitude modulation techniques discussed in the next section can be used for displaying a large number of gray shades with minimum number of time intervals.

3. Amplitude modulation techniques

A large number of gray shades is desirable for good reproduction of images. Amplitude modulation [1], also known as pulse height modulation [2] can be used to display a large number of gray shades in passive matrix LCDs.



Figure 8. Photograph of a 16×16 matrix LCD using successive approximation technique to display eight gray shades.

3.1 Principle

Suppose amplitude of the column voltage is proportional to the gray shade of pixel in the selected row i . The expression for rms voltage across a pixel is

$$V_{\text{rms}} = \sqrt{\frac{(V_r - V_{ij})^2 + \sum_{k \neq i} V_{kj}^2}{N}} = \sqrt{\frac{V_r^2 - 2V_r V_{ij} + \sum_{k=1}^N V_{kj}^2}{N}} \quad (8)$$

In this equation both the second term as well as the last term contains V_{ij} . Hence modulating the column voltage directly alters the rms voltage across all the pixels in that column, instead of controlling the rms voltage across a pixel in the selected row. This is because the amplitude of the column voltage is not independent of the data as in the case of line-by-line addressing wherein only the sign of the voltage depends on the data. Introducing N dummy rows in a matrix display with N rows as shown in figure 9 is useful to surmount this problem. Let g be the gray shade to be displayed in the selected row, g ranges from -1 to $+1$. Here, -1 corresponds to an ON pixel and $+1$ to an OFF pixel. A data of either $+\sqrt{1-g^2}$ or $-\sqrt{1-g^2}$ may be assigned to the corresponding dummy row. Magnitude of the data for a dummy row is same and it differs only in sign. Choice of the dummy data is such that sum of the square of the data of a row and the corresponding dummy row is a constant and is equal to the square of the maximum of the gray shade data. This value is 1 here since the normalized gray shade data ranges from $+1$ (for OFF pixels) to -1 (for ON pixels). Now the matrix of $2N$ rows can be scanned line by line while the column voltage applied is proportional to the gray shade data ($g \cdot V_c$ and $\sqrt{1-g^2} \cdot V_c$). The rms voltage across a pixel will be

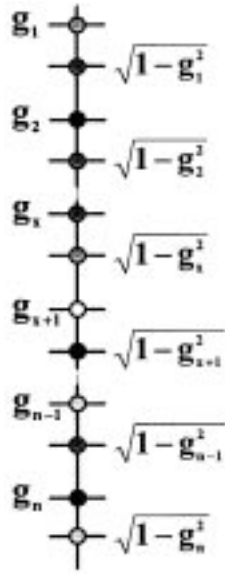


Figure 9. Principle of amplitude modulation (dummy rows).

$$\begin{aligned}
 V_{\text{rms}} &= \sqrt{\frac{(V_r - gV_c)^2 + (\sqrt{1 - g^2})^2 V_c^2 + (N - 1) \cdot (g^2 + (\sqrt{1 - g^2})^2) V_c^2}{2N}} \\
 &= \sqrt{\frac{V_r^2 - 2gV_rV_c + NV_c^2}{2N}}. \tag{9}
 \end{aligned}$$

This expression is almost the same as that in eq. (1). Selection ratio is also the same as that of eq. (3). The term $2N$ in the denominator in this equation (instead of N in eq. (1)) results in an increase of supply voltage by a factor $\sqrt{2}$ as compared to that of line-by-line addressing for binary images. Amplitude modulation overcomes this problem by using two time intervals.

3.2 Amplitude modulation – split time interval

It is well-known that supply voltage of the drive electronics decreases when more than one line is selected simultaneously [9] using orthogonal functions. This idea may also be used to reduce the supply voltage of the amplitude modulation based on line-by-line addressing. Consider selecting a row along with its dummy row simultaneously with waveforms derived from orthogonal functions. Here two rows are selected simultaneously with a Hadamard matrix of order 2

$$H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}. \tag{10}$$

The data in a row and the corresponding dummy row can be any one of the following: They are either

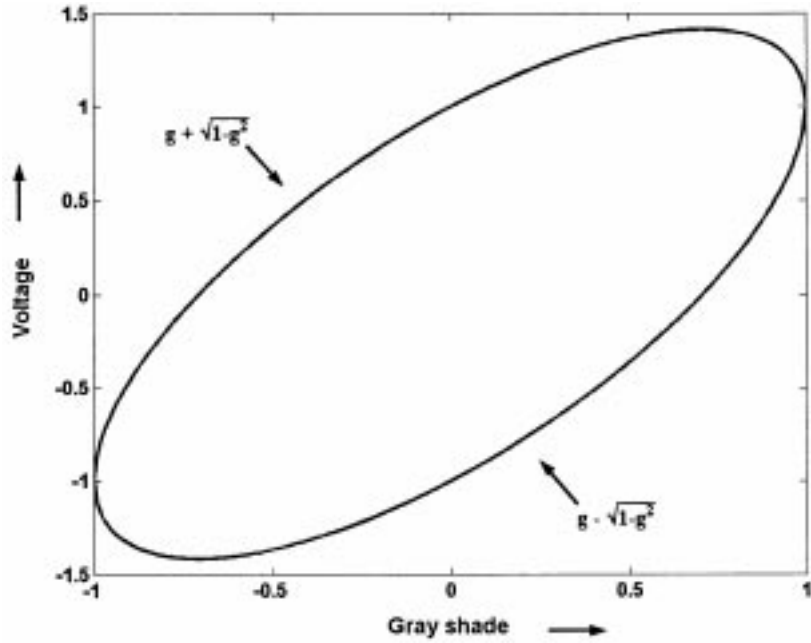


Figure 10. Normalized column voltage for split time interval.

$$\left[\frac{g}{\sqrt{1-g^2}} \right] \quad \text{or} \quad \left[-\frac{g}{\sqrt{1-g^2}} \right]. \quad (11)$$

Just the sign of the data in the dummy row is different in the data vectors in the above expression. Column voltages (C_1 and C_2) are proportional to orthogonal transform of the data

$$\begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \cdot \left[\frac{g}{\sqrt{1-g^2}} \right] = \begin{bmatrix} g + \sqrt{1-g^2} \\ g - \sqrt{1-g^2} \end{bmatrix} \cdot V_c. \quad (12)$$

This corresponds to the expressions in eq. (18). The other option for the column voltages is

$$\begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \cdot \left[-\frac{g}{\sqrt{1-g^2}} \right] = \begin{bmatrix} g - \sqrt{1-g^2} \\ g + \sqrt{1-g^2} \end{bmatrix} \cdot V_c. \quad (13)$$

Column voltages for these two cases shown above are same except that the time interval during which they are applied is interchanged. Figure 10 gives plot of column voltage as a function of gray shade data g and these two together trace an ellipse. Polarities of both the row and column voltages are reversed periodically to ensure long life of the display and the column voltages trace another ellipse (not shown in the figure). The other two possibilities of data are shown in expression (14) and they are obtained by interchanging position of a row with the corresponding dummy row and also by changing the sign of the dummy data. They are either

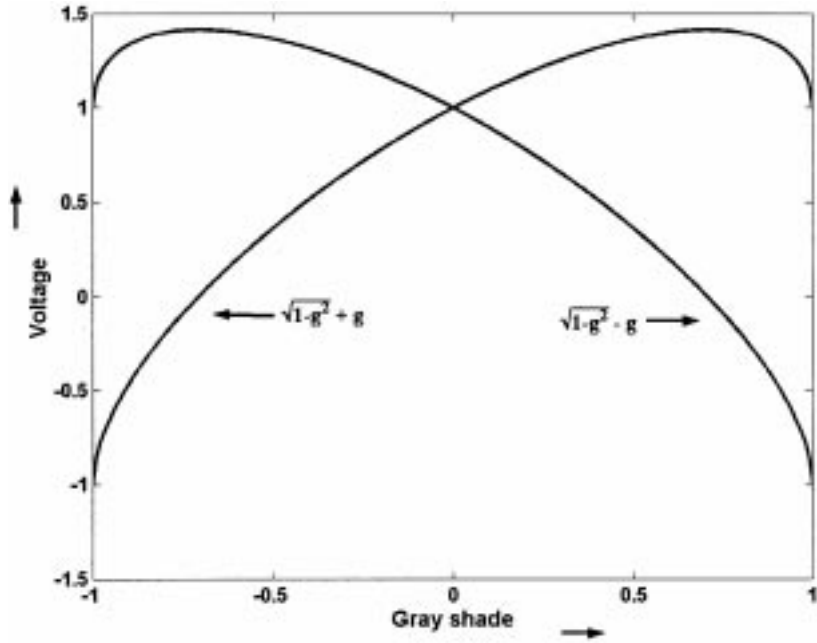


Figure 11. Normalized column voltages (option 2).

$$\begin{bmatrix} \sqrt{1-g^2} \\ g \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} -\sqrt{1-g^2} \\ g \end{bmatrix}. \quad (14)$$

The corresponding column voltages are as shown in the following equations:

$$\begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} \sqrt{1-g^2} \\ g \end{bmatrix} = \begin{bmatrix} \sqrt{1-g^2} + g \\ \sqrt{1-g^2} - g \end{bmatrix} \cdot V_c. \quad (15)$$

Figure 11 gives the plot of these two column voltages and they are half segments of two ellipses. The other two column voltages are

$$\begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} -\sqrt{1-g^2} \\ g \end{bmatrix} = \begin{bmatrix} -\sqrt{1-g^2} + g \\ -\sqrt{1-g^2} - g \end{bmatrix} \cdot V_c. \quad (16)$$

Figure 12 shows the plot of these column voltages with reference to the gray shade g and they form the segments of two different ellipses. Needless to say that polarity of the row and column voltages is to be reversed periodically to ensure a DC-free operation. In fact the column voltages in figure 12 are the other segments of ellipses in figure 11 and only the sign of these voltages is changed. The fluctuations of DC voltages between frames is lower while using eq. (15) or (16) as compared to that of eq. (12) or (13) because the row waveforms in the first case will have both the polarity within a frame. All these schemes with minor variations of row and column waveform may be classified under split time interval method since a row select time is split into two time intervals. The rms

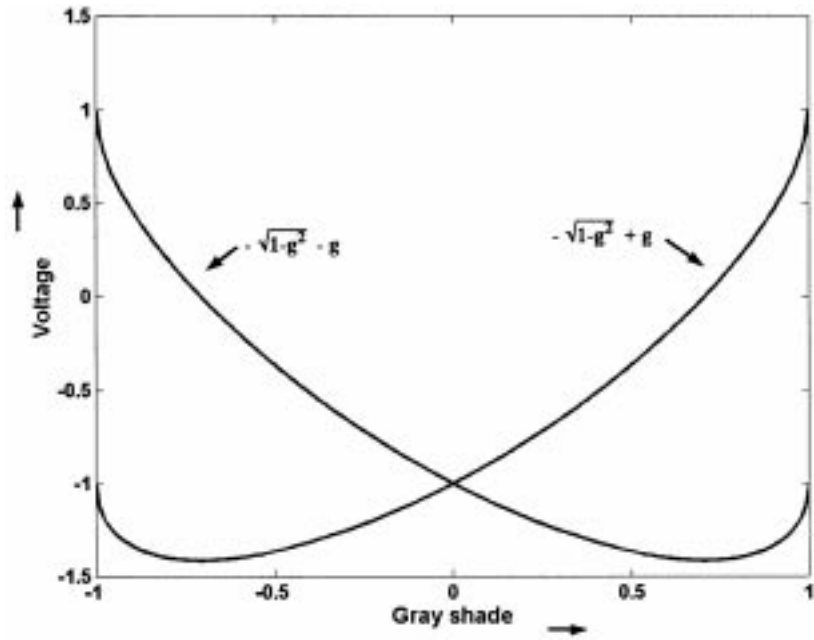


Figure 12. Normalized column voltages (option 3).

voltage across a pixel with column voltages $(g + \sqrt{1 - g^2})V_c$ during one time interval and $(g - \sqrt{1 - g^2})V_c$ in the other time interval in a display driven by amplitude modulation is

$$\sqrt{\frac{(V_r - (g - \sqrt{1 - g^2})V_c)^2 + (V_r - (g + \sqrt{1 - g^2})V_c)^2 + (N - 1)((g - \sqrt{1 - g^2})^2 + (g + \sqrt{1 - g^2})^2)V_c^2}{2N}}. \quad (17)$$

The expression given above simplifies to

$$V_{\text{rms}} = \sqrt{\frac{V_r^2 - 2gV_rV_c + NV_c^2}{N}}. \quad (18)$$

This expression is the same as that of eq. (1) except for the inclusion of gray shades. Hence the selection ratio as well as the supply voltage are the same as those of the line-by-line addressing for displaying binary images. The second term in the above expression contains g and hence the rms voltage across the selected pixel depends on g . The first and third terms which are common to all the pixels in a column are independent of g . Typical waveforms of amplitude modulation technique using split time interval are shown in figure 13. Split time interval technique needs $(2g - 2)$ voltages for displaying g gray shades. A photograph of a display using amplitude modulation for gray shades is shown in figure 14.

Gray shades in liquid crystal displays

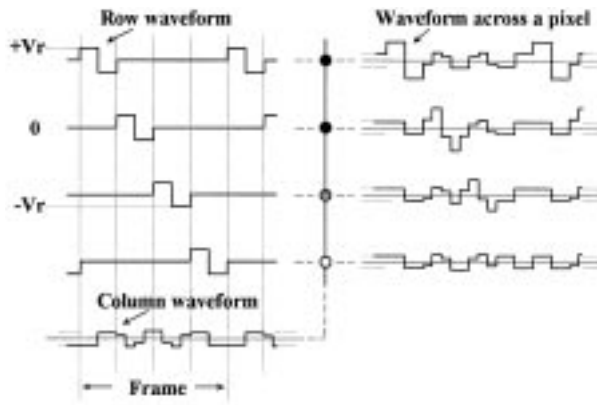


Figure 13. Amplitude modulation (split time interval).

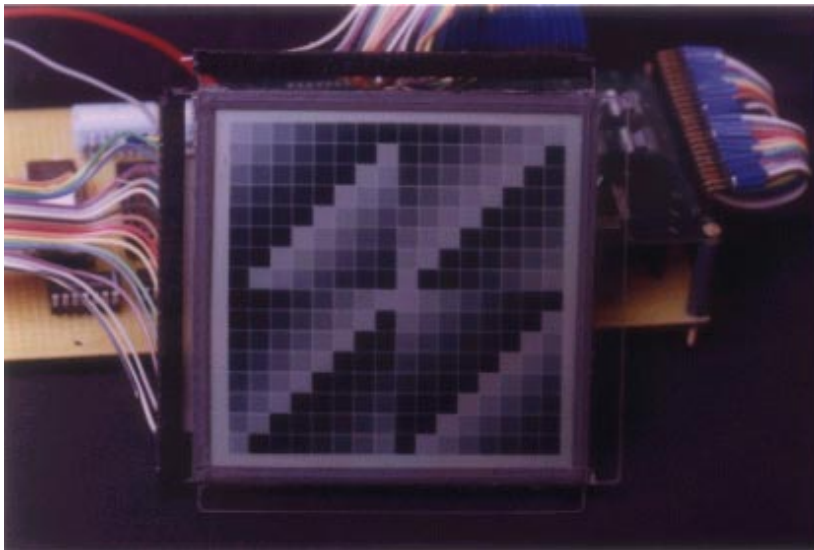


Figure 14. Photograph of a 16×16 matrix LCD displaying eight gray shades using amplitude modulation.

3.3 Pulse height modulation – full time interval

An alternate approach to split time interval would be to introduce just one dummy row in the matrix display instead of N dummy rows. The data for the dummy row is

$$\text{data}_{\text{dummy}} = \sqrt{N - \sum_{i=1}^N g_i^2}, \quad (19)$$

where g_i is the data to be displayed in row i .

The matrix display is scanned as if there are $(N + 1)$ rows in the passive matrix display. This approach is called pulse height modulation – full time interval [2]. The rms voltage across a pixel is given by

$$V_{\text{rms}} = \sqrt{\frac{(V_r - g_{ij}V_c)^2 + \sum_{k \neq i} g_{kj}^2 V_c^2 + \left[\sqrt{N - \sum_{i=1}^N g_i^2} \right]^2 V_c^2}{(N + 1)}} \\ = \sqrt{\frac{V_r^2 - 2g_{ij}V_rV_c + NV_c^2}{(N + 1)}}. \quad (20)$$

This expression is similar to that of eq. (18) except that the denominator is $(N + 1)$ instead of N in eq. (18). This increases the supply voltage by a factor $\sqrt{(N + 1)/N}$ which is almost 1 for large values of N and hence has no practical consequence. However, computation of data for the dummy row needs all the data in a frame. Computation of dummy data involves $N \cdot M$ multiplications (for squaring g), $N \cdot M$ additions and subtraction and M square roots performed for each frame. Here M is the number of columns in the display. This is too demanding in terms of both speed and cost. Split time interval on the other hand needs $N \cdot M$ multiplication and $N \cdot M$ subtractions and $N \cdot M$ square roots to be computed in each frame. However, storing the pre-computed values of $\pm[g + \sqrt{(1 - g^2)}]$ and $\pm[g - \sqrt{(1 - g^2)}]$ once for all for finite number of gray levels in a memory can eliminate this computation. About $2g$ values may be stored and used as column signals to display g gray shades. This approach is not feasible with full time interval method because the number of pre-computed values is large even for finite number of gray shades. In summary the amplitude modulation with split time interval approach is more feasible to realize than the pulse height modulation with full time interval.

3.4 Amplitude modulation for multi-line addressing

The principle of amplitude modulation can be extended to multi-line addressing. The data for displaying a gray shade g is $[g + \sqrt{(1 - g^2)}]$ in one frame and $[g - \sqrt{(1 - g^2)}]$ in another frame and the corresponding column voltages for the two frames are computed as shown here:

$$\begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \cdot \begin{bmatrix} g_1 + \sqrt{(1 - g_1^2)} \\ g_2 + \sqrt{(1 - g_2^2)} \\ g_3 + \sqrt{(1 - g_3^2)} \\ g_4 + \sqrt{(1 - g_4^2)} \end{bmatrix} V_c \quad (21)$$

$$\begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \cdot \begin{bmatrix} g_1 - \sqrt{(1 - g_1^2)} \\ g_2 - \sqrt{(1 - g_2^2)} \\ g_3 - \sqrt{(1 - g_3^2)} \\ g_4 - \sqrt{(1 - g_4^2)} \end{bmatrix} V_c \quad (22)$$

This is similar to split time interval method. Alternatively a dummy row can be introduced for each sub-group as in the case of full time interval method and the corresponding column voltages are computed as follows:

$$\begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \cdot \begin{bmatrix} \sqrt{(3 - g_1^2 - g_2^2 - g_3^2)} \\ g_1 \\ g_2 \\ g_3 \end{bmatrix} V_c. \quad (23)$$

The number of voltage levels is large for the multi-line addressing techniques as compared to split time interval technique based on line-by-line addressing.

4. Conclusion

The principle underlying the development of amplitude modulation has been presented. The technique has been compared with other techniques for displaying gray shades. Amplitude modulation with split time interval is well-suited for displaying a large number of gray shades without flicker. Selection ratio as well as the supply voltage of this technique is the same as that of line-by-line addressing. However, the large number of voltage levels in the column waveform (about $2g$ for displaying g gray shades) needs analog type column drivers that consume more power as compared to digital drivers with limited number of voltage levels. Further research and development is necessary to come up with a technique better than amplitude modulation for displaying gray shades in rms responding passive matrix liquid crystal displays.

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