Discrete Cosine Transform for Driving Liquid Crystal Displays

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***Abstract*—Despite rapid advances in science and technology of liquid crystal display (LCD); elimination of motion-related artifacts and preservation of color purity in moving images have remained elusive because gray-scale to gray-scale response time, i.e., time taken to switch pixels from one gray-scale to another depends on the initial and final gray shades. A technique wherein gray scale to gray scale response times are less dependent on the initial and final gray shades as compared to other addressing techniques for driving matrix LCD is reported. We also found that the response times are about the same as that of a pixel driven with simple square waveforms and, therefore, the effect of duty cycle due to matrix addressing is minimal with distributed waveforms of this technique.**

***Index Terms*—Gray shades, liquid crystal displays (LCDs), matrix addressing, multiplexing.**

I. Introduction

PASSIVE-MATRIX type liquid crystal display (LCD) are used in cell phones, MP3 players and other portable gadgets because they have simple structure and cost less as compared to active matrix displays with a thin film transistor (nonlinear element) embedded in each pixel. LCD exhibit root mean square (rms) response to the electric field when the period of addressing waveforms is smaller than the time taken by liquid crystal molecules to respond and orient to the time variant electric field. Pixels in each row of a matrix display are connected together to a row address line (scanning line) so that they can be selected simultaneously with a select pulse or a waveform. Similarly, a column address line (data line) connects all the pixels in that column to multiplex data assigned to the state of pixels in that column. Hence, each pixel in a matrix display can be uniquely addressed with a scanning line and a data line. Scanning waveforms are equivalent to "carriers" and the data waveforms are equivalent to "multiplexed signal" in a communication system. Orthogonal functions are used to multiplex and de-multiplex the state of pixels in all the addressing techniques for driving passive-matrix displays [1]–[11]. Intrinsic nonlinear electro-optic characteristic of LCD is useful to de-multiplex or decode the multiplexed signal. Amplitude of scanning and data waveforms is optimized to obtain good contrast in the display [1], [2]. Response times depend on the liquid crystal mixture, cell gap (thickness of the liquid crystal layer in the display), waveform across the pixel as well as the initial and final grayscales [3]. Rectangular block pulses [1], [2] Rademacher functions [4], Hadamard matrices [5], Walsh functions [6], and wavelets [7]–[10] are used to drive passive-matrix displays. Response times have a wide range dependence on the initial and final gray shades in displays driven with most of the addressing techniques [8]–[11]. Discrete cosine transform (DCT) is well known for its high-energy compaction ratio and the possibility of using DCT to drive matrix LCD has been demonstrated [12]. We have used discrete cosine transform (DCT) with some minor modification to drive matrix LCD and the gray scale to gray scale response times are more uniform as compared to any other addressing technique to date. Hence, fast moving objects can be displayed with less visual artifacts because all pixels will switch more or less simultaneously during transitions from one frame to another. Similarly, color purity will be better when the color sub-pixels switch simultaneously.

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II. Technique and Analysis

The set of orthogonal Chebyshev polynomials $\Gamma_k(m)$, form the basis vector elements of DCT [12]

$$\Gamma_k(m) = \sqrt{\frac{2}{M}} \cdot \cos\frac{(2m+1)\cdot k\cdot\pi}{2M}, \quad \begin{cases} \text{for } k = 1,2,\ldots,(M-1) \\ m = 0,1,\ldots,(M-1). \end{cases} \tag{1}$$

Discrete cosine transform of a discrete data sequence $X(m); m = 0, 1, \ldots (M-1)$ is defined [13], [14] as follows:

$$G_x(k) = \sqrt{\frac{2}{M}} \sum_{m=0}^{M-1} X(m) \cos\left(\frac{(2\cdot m+1)\cdot k\cdot\pi}{2M}\right)$$
$$\text{where} \quad m = 0,1,\ldots,(M-1), \quad k = 1,2,\ldots,(M-1). \tag{2}$$

Amplitude of each polynomial $\Gamma_k(m)$ is multiplied by $(\sqrt{2})^{(k-1)}$ so that the energy of each function is proportional to the weight of a grayscale bit (bit-k) of pixels in a matrix display. The modified polynomials also satisfy the orthogonal condition as shown in

$$\sum_{m=0}^{M-1} (\sqrt{2})^{(k-1)}\Gamma_k(m)(\sqrt{2})^{(l-1)}\Gamma_l(m) = \begin{cases} 2^{(k-1)}, & \text{for } k = l \\ 0, & \text{for } k \neq l. \end{cases} \tag{3}$$

Let us consider a matrix display with N rows and arbitrary number of columns. Each column is independent of the other if we multiplex the information through column address lines.

Let the rows: $(i+1), (i+2), \ldots, (i+M-1)$ be selected simultaneously with $(M-1)$ waveforms of

$$x_{i+k}(m) = V_r(\sqrt{2})^{k-1}\Gamma_k(m);, \qquad k = 1, 2, \ldots, (M-1). \tag{4}$$

The remaining $(N-M+1)$ non-selected rows in the matrix display are connected to ground potential, i.e., $(V_r = 0)$. Let $d_{k,i+k}; k = 1, 2, \ldots, (M-1)$ be the grayscale bit of pixels that are located at the intersection of selected rows and column "j" and let the data assigned to them be $d_{k,i+k} = +1$ for "logic-0" and $d_{k,i+k} = -1$ for "logic-1." Select waveform of row: $(i+k)$ is multiplied with data assigned to the bit-k of a pixel in $\mathrm{row}(i+k)$ and $(M+1)$ such products are added to obtain the column (data) waveforms as shown in

$$y_j(m) = V_c \sum_{k=1}^{M-1} d_{k,(i+k)}(\sqrt{2})^{(k-1)}\Gamma_k(m). \tag{5}$$

Here, the least significant bit (LSB) is used for the row: $(i+1)$ and the most significant bit is used for the row: $(i+M-1)$ and the intermediate bits for the $(M-3)$ selected rows. It is equivalent to modified discrete cosine transform (MDCT) of just one bit of gray shade of pixels in the selected rows. The terms V_r and V_c are used to control the amplitude of row and column waveforms respectively to achieve good contrast in the display. Both the row and column waveforms are applied to the matrix display and information in the multiplexed column waveform is decoded using the intrinsic nonlinear characteristics of RMS responding devices like LCD. Typical waveforms when 3-rows are selected simultaneously to display 8-grayscales are shown in Fig. 1. Let the duration of each time interval be T. Waveform across the pixel is the difference of (4) and (5) and energy delivered during M-time intervals to a pixel located at the intersection of row: $i+l$ and a column is

$$E_{l,i+l}(m) = T \sum_{m=0}^{M-1} \left(V_r(\sqrt{2})^{l-1}\Gamma_l(m) - V_c \sum_{k=1}^{(M-1)} (\sqrt{2})^{k-1}\Gamma_k(m) d_{k,i+k} \right)^2. \tag{6}$$

Orthogonal property of select waveforms is used to simplify the expression to

$$E_{l,i+l}(m) = T\left(V_r^2 2^{(l-1)} - 2^l V_r V_c d_{l,i+l} + V_c^2(2^{M-1} - 1)\right). \tag{7}$$

The second term in (7) depends on the grayscale bit; whereas the first and last terms are independent of the data bit. Hence the energy delivered to the pixel during the M time intervals is proportional gray shade bit. The constant term of (7) will not affect demultiplexing because it is possible to accumulate some voltage even across an OFF pixel. Electro-optic response of liquid crystal displays has a threshold voltage and the pixels will not respond to voltages below the threshold voltage. Waveforms applied to columns will appear across pixels in non-selected rows that are connected to the ground potential because it is not possible to isolate non-selected pixels in passive matrix LCD due to its simple structure. Energy delivered to a pixel if it is not selected during M-time intervals can be obtained by substituting $V_r = 0$ as follows:

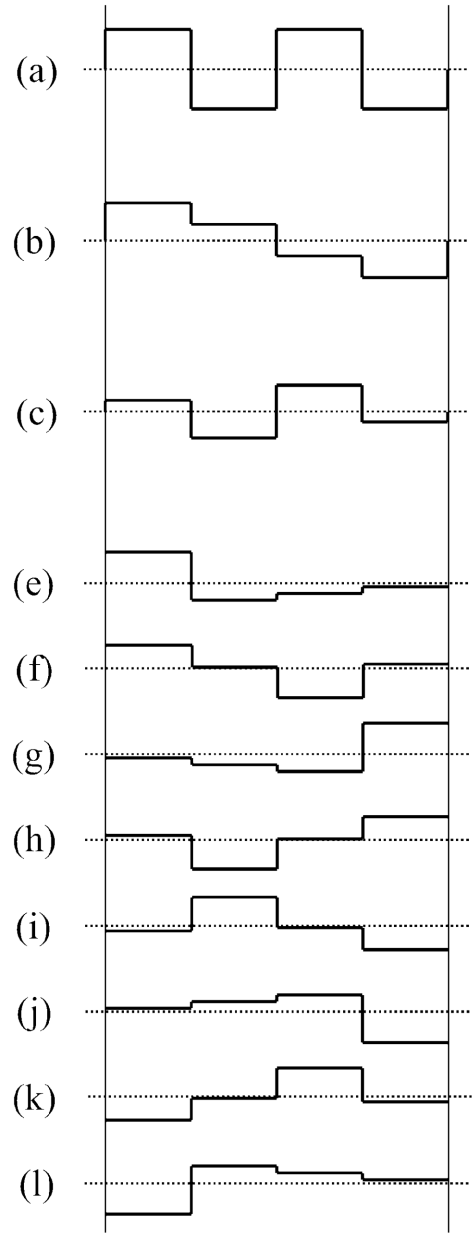

Fig. 1. Select and data waveforms that are based on MDCT for displaying eight gray shades in rms responding displays are shown. (a)-(c) Select waveforms obtained by modifying the DCT; energies of these waveforms are in the ratio 4:2:1. (e)-(l) Data waveforms for the grayscales (000) to (111). Note that waveforms (l),(k),(j) and (i) can be obtained by multiplying the waveforms (e)–(h), respectively, with -1 because the respective gray shade bits complement each other.

$$E_{n\_s} = T\left(V_c \sum_{k=1}^{M-1} (\sqrt{2})^{(k-1)}\Gamma_k(m) d_{k,i+k}\right)^2 = T(2^{(M-1)} - 1)V_c^2. \tag{8}$$

Energy delivered to the non-selected pixels is independent of the data bits because the value assigned to the bits is (± 1) i.e., the magnitude of the voltages is same. It is clear from the expression in (8) that a crosstalk-free display can be achieved when

MDCT is used for addressing LCD because the energy delivered to the non-selected pixels is independent of state of the pixels in the selected row(s). An address cycle gets completed when N rows in the matrix display are selected with $(M-1)$-select waveforms once, i.e., when each row is selected with waveforms $x_{i+k}(m); k = 1, 2, \ldots, (M-1)$. The address duty cycle is higher by a factor $(M-1)$ as compared to that of the line-by-line addressing. Typical addressing waveforms are shown in Fig. 2. It is not necessary that N should be an integral multiple of $(M-1)$. In case N, the number of address lines is not an integral multiple of $(M-1)$ then the following scheme can be adopted. Let rows $(i+l)$ wherein $l = 1, 2, \ldots, (M-1)$ be selected with waveforms that are proportional to $(\sqrt{2})^{(l-1)}\Gamma_l(m)$ for M time intervals. Then the select waveforms are shifted by one row so that rows $(i+1+l)$ wherein $l = 1, 2, \ldots, (M-1)$ are selected with waveforms that are proportional to: $(\sqrt{2})^{(l-1)}\Gamma_l(m)$ during M-time intervals. An address cycle consists of N such shifts and the total duration is $(M \cdot N)$ time intervals and each row is selected during $(M-1) \cdot M$ time intervals. Energy delivered to the pixel during $(M-1) \cdot M$-time intervals when the corresponding row is selected with $(M-1)$ discrete cosine functions is obtained by adding the energy corresponding to each of the grayscale bits.

$$E_{i,j\_s} = \sum_{l=1}^{M-1} E_{l,i}(m) = \sum_{l=1}^{M-1}\left(2^{(l-1)}V_r^2 - 2^l V_r V_c d_{l,i} + (2^{(M-1)}-1)V_c^2\right) \quad (9)$$

$$E_{i,j\_s} = (2^{(M-1)}-1)\left(V_r^2 + (M-1)\cdot V_c^2\right) - \sum_{l=1}^{M-1} 2^l d_{l,i} V_r V_c \quad (10)$$

Similarly, energy delivered to the pixel in row-i during $M((N/(M-1))-1)$ time intervals when the corresponding row is not selected is obtained as shown in the following equations:

$$E_{i,j\_ns} = \left(\frac{N}{(M-1)} - 1\right) \times \sum_{m=0}^{M-1}\left(V_c \sum_{k=1}^{M-1} d_{k,i+k}(\sqrt{2})^{(k-1)}\Gamma_k(m)\right)^2 \quad (11)$$

$$E_{i,j\_ns} = V_c^2\left(\frac{N}{M-1} - 1\right)\sum_{k=1}^{M-1}(2^{(M-1)}-1) = V_c^2\left(\frac{N}{M-1} - 1\right)(M-1)(2^{(M-1)}-1). \quad (12)$$

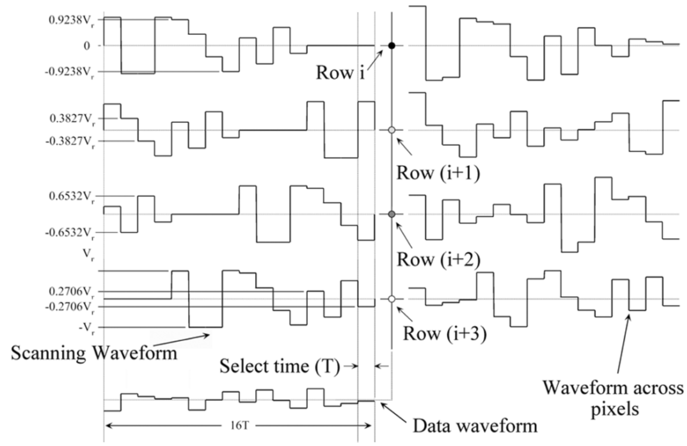

Fig. 2. Typical waveforms when MDCT is used to scan the display and select pulses are clustered.

Hence, energy delivered to a pixel when it is not selected is independent of the data of the selected pixels. RMS voltage across the pixel is given by (13) and (14), shown at the bottom of the page.

RMS voltage across a pixel when

$$d_{k-1,j} = +1 \; \forall \; k = 1, 2, \ldots, (M-1)$$

i.e., an OFF pixel is

$$V_{\mathrm{OFF}}(\mathrm{RMS}) = \sqrt{\frac{(2^{M-1}-1)(V_r^2 - 2V_rV_c + NV_c^2)}{MN}} \quad (15)$$

Similarly, RMS voltage across a pixel when

$$d_{k-1,j} = +1 \; \forall \; k = 1, 2 \ldots, (M-1)$$

is as follows:

$$V_{\mathrm{ON}}(\mathrm{RMS}) = \sqrt{\frac{(2^{M-1}-1)(V_r^2 + 2V_rV_c + NV_c^2)}{MN}}. \quad (16)$$

The selection ratio, ratio of the RMS voltages across the ON pixel to that of the OFF pixel in this technique is a maximum when $V_r = \sqrt{N} \cdot V_c$ and it is same as the maximum achievable by any addressing technique [11], [12]

$$\frac{V_{\mathrm{ON}}(\mathrm{RMS})}{V_{\mathrm{OFF}}(\mathrm{RMS})} = \sqrt{\frac{\sqrt{N}+1}{\sqrt{N}-1}}. \quad (17)$$

The technique was demonstrated by displaying eight gray shades [12]. A photograph of a display system is shown in Fig. 6. The driver circuit of passive matrix LCD consists of row driver circuit, column driver circuit, voltage level generator and the controller. Both row and column drivers have analog

$$V_{\mathrm{pixel}}(\mathrm{RMS}) = \sqrt{\frac{E_{i,j\_s} + E_{i,j\_ns}}{M \cdot N}} \quad (13)$$

$$V_{\mathrm{pixel}}(\mathrm{RMS}) = \sqrt{\frac{(2^{(M-1)}-1)(V_r^2 + NV_c^2) - \sum_{l=1}^{M-1} 2^k d_{l,i} V_r V_c}{MN}} \quad (14)$$

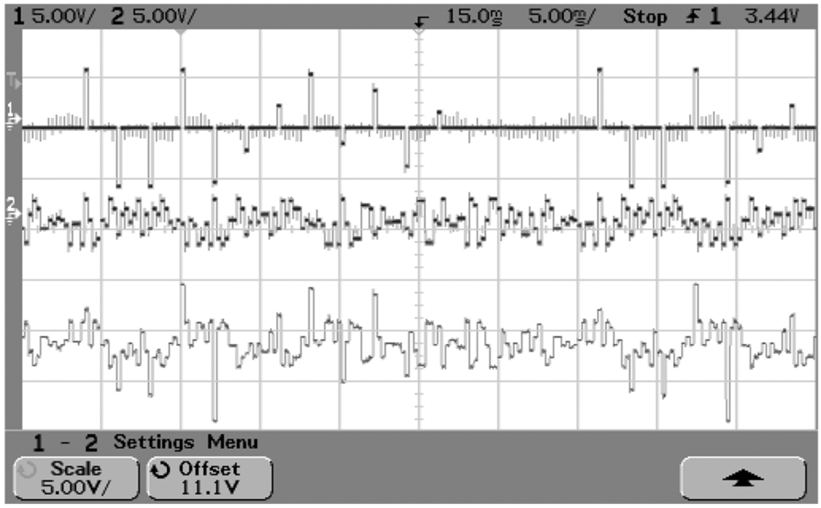

Fig. 3. Addressing waveforms when select pulses are distributed (separated by at least seven time intervals from each other). Row waveform appears at the top and it is followed by column waveform. Waveform across a pixel (third waveform) is the difference of the first and the second waveforms.

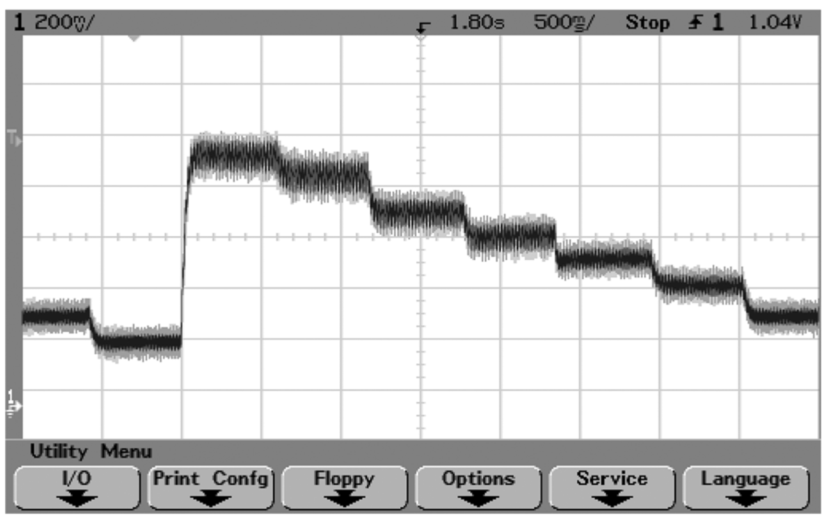

Fig. 4. Light transmission through a pixel when the RMS voltage across a pixel is varied to display 8 gray shades with MDCT. Switching time (response time) is about three cycles and it is independent of initial and final gray shade.

multiplexers that select voltages to be applied to the matrix display. The controller is implemented in a CPLD (complex programmable logic device). The modified DCT matrix for multiplexing 3-bits is as follows:

$$\begin{bmatrix} 1 & -1 & -1 & 1 \\ 0.924 & 0.383 & -0.383 & -0.924 \\ 0.271 & -0.653 & 0.653 & -0.271 \end{bmatrix}.$$

The MDCT for the finite set of data are computed during the design stage and programmed into the VLG (voltage level generator; a resistor network) and, therefore, it is not necessary to compute the MDCT while scanning the display. Row waveforms have 11 voltages and drivers that are capable of applying 1 of the 11 voltages to the 32 rows are necessary for direct implementation of the driver circuit. However, drivers that are capable of applying 1-out-of-4 voltages are adequate when four 4:1 analog multiplexers are used to feed voltages corresponding to select vectors to the 32 stages of the row drivers because just three select voltages and a non-select voltage are applied to the matrix display at a given instant of time. We have used "off-the-shelf" row drivers that are capable of applying any one of eight voltages along with three 2:1 analog multiplexers that are common to all 32 stages of the row driver board. Similarly, display drivers that are capable of applying one-out of eight voltages is used as column drivers along with eight numbers of 2:1 analog multiplexers to apply any one of the 16 voltages because at a given instant of time just eight voltages need to be applied. The eight 2:1 analog multiplexers are common to all the stages of the column drivers. Additional information on hardware implementation of the technique can be found in [12].

The display was refreshed at 50 Hz and the minimum frequency to avoid flicker is 40 Hz. The display is not optimized for response time and faster response times may be achieved with other liquid crystal mixtures. Response times were measured by applying row and column waveforms from the prototype to a cell filled with RO-TN-623. Thickness of the cell was 5.6 μm. The controller in the prototype was programmed to switch the

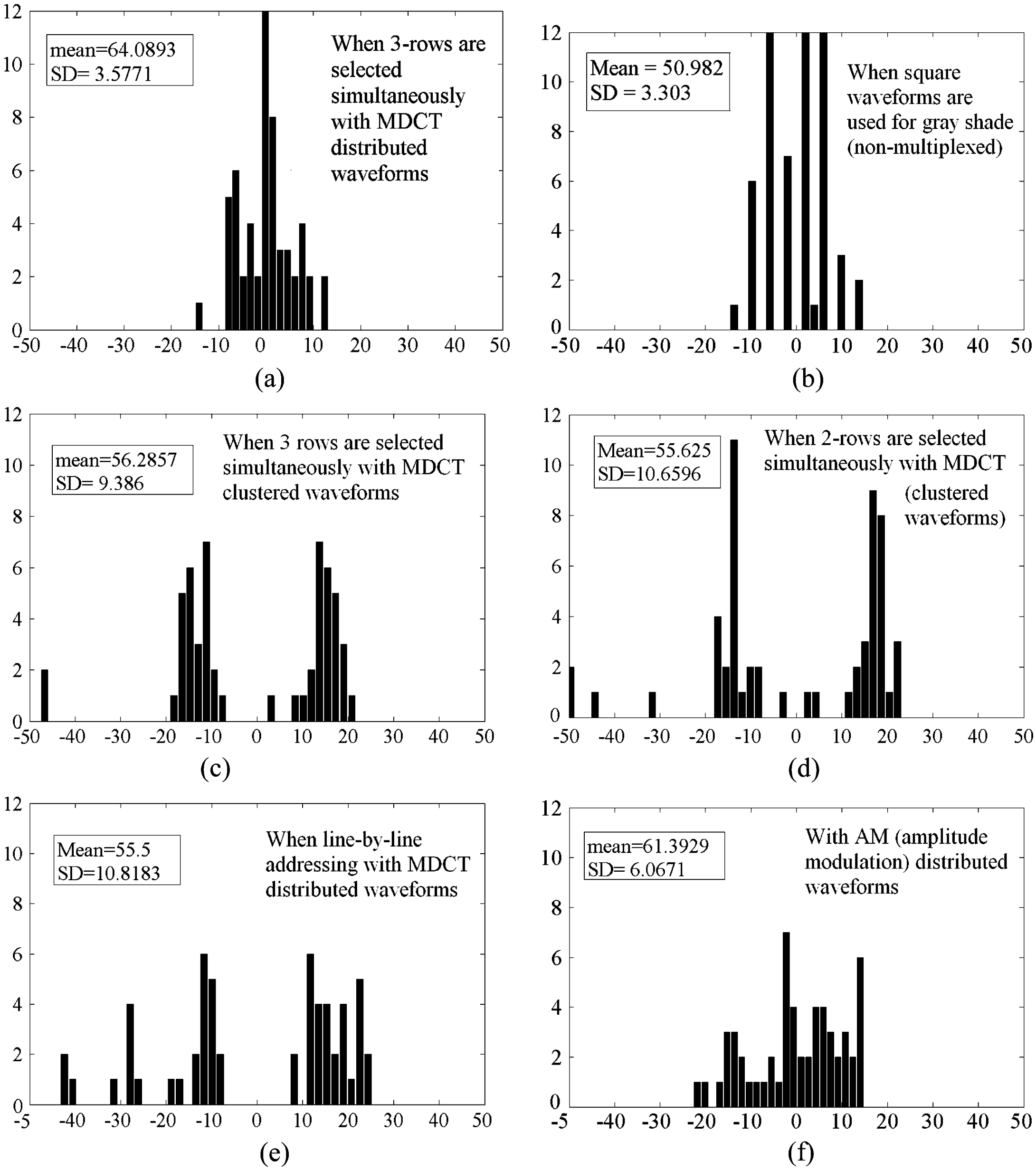

Fig. 5. Number of occurrences versus percentage deviation from the mean response time (in milliseconds) when pixels are switched from one gray shade to another of a pixel driven by: (a) MDCT with distributed waveforms when 3 rows are selected simultaneously: (b) with square waveforms: (c) MDCT with clustered waveform 3-rows are selected simultaneously; (d) MDCT with two rows selected simultaneously; (e) line-by-line addressing technique that is based on MDCT; and (f) amplitude modulation technique [4].

pixel to different gray shades and the change in light transmission through the cell was captured using a photo detector. The output of the photo detector was acquired using a digital storage oscilloscope to measure the response times.

III. Results

There are several ways to scan the matrix display. A subgroup may be selected with all the select vectors (columns of the orthogonal matrix) and rotated versions of select vectors before selecting another subgroup leading to clustering of select pulses, as shown in Fig. 2. Alternately, each subgroup can be selected with just one select vector and it results in distributed select pulses shown in Fig. 3. It is very useful to suppress the frame response and to eliminate flicker even with relatively low refresh rates as compared to the clustered waveforms. The addressing technique with distributed select pulses of MDCT also achieves uniform response times, as shown in Fig. 4. Response times were measured by switching the pixels from one gray to another with distributed waveforms shown in Fig. 3. Light transmission through a pixel when it is switched from one gray scale to another is shown in Fig. 4. Distribution of response times (28 rise times and equal number of fall times) that were measured is shown in Fig. 5(a).

Response times of the same cell for several variants of the technique and amplitude modulation for 8 gray shades are also shown in Fig. 5(c)–(f) for comparison. In order to see the effect of addressing technique on response times; we applied square waveforms (100 Hz) with their RMS voltage equal to that of the

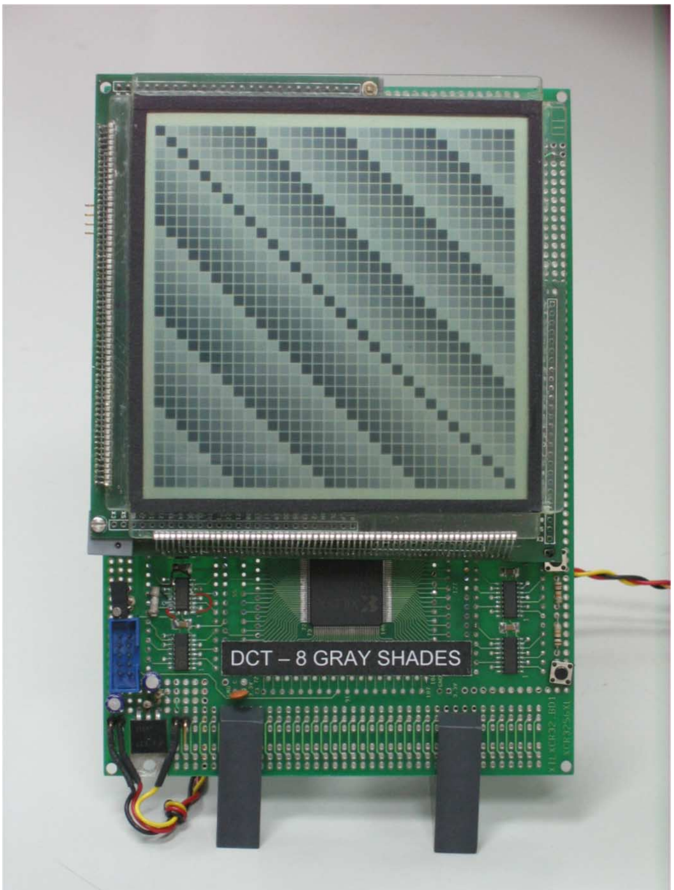

Fig. 6. Photograph shows 8-grayscales obtained by driving a 32×32 matrix display with waveforms of MDCT.

eight gray shades in a matrix display with 32 address lines; see Fig. 5(b). Response times measured under this condition were about the same as that obtained when the matrix display is multiplexed with distributed waveforms of MDCT. It is interesting to note that the effect of duty cycle in the addressing waveform is not seen when DCT is used because response times obtained with the addressing waveforms are very close to the response times when pixels are driven with continuous square waveforms (without duty cycle). Hence the response times are not affected by DCT based addressing waveforms. The technique retains the advantages of multi-line addressing viz. higher address duty factor, low supply voltage, and suppression of frame response.

IV. Conclusion

Modified DCT has paved way to achieve uniform response times in passive matrix LCD leading to elimination of motion related artifacts and better color purity of images. It is also important to note that the discrete cosine transform is used in compression techniques for static as well as video images as shown by Lawrence *et al.* [15]. Column waveforms of multi-line addressing techniques are proportional to the one-dimensional transform of images, and hence, hardware and time that are necessary for decoding the compressed images can be eliminated when DCT is used for addressing the display. Aperture available for light transmission in a pixel decreases as we increase the resolution of active matrix LCD due to the space occupied by the thin-film transistors at each pixel and driving the display by combining active and passive-matrix addressing as proposed by Kuijk *et al.* [16] is another possible extension of this technique. If "s" is the number of lines that are selected simultaneously then the number of thin film transistors can be reduced by a factor s and this approach is very useful for high resolution displays such as medical displays. Relatively large amplitude of the passive addressing waveforms used for selecting s-rows will have the same effect as the waveforms that are modified to improve the response time of active matrix LCD [17]. Pulsed nature of the addressing waveforms in waveforms of passive addressing is useful in achieving uniform response times.

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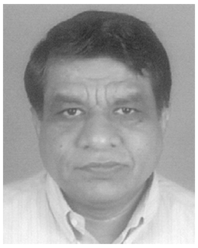

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Prof. Ruckmongathan is a member of Society for Information Display.