LCD Response Time Evaluation in the Presence of Backlight Modulations

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Abstract

This paper introduces a method for evaluation of the response times of LCDs when the measured temporal luminance function is dominated by periodic fluctuations induced by the pulse-width modulation (PWM) circuit used for dimming of the backlight luminance. We present our implementation of deconvolution of the transition between the stationary states which is slowed-down by the process of convolution (i.e. *moving window averaging*). With this method considerable errors in the evaluation of *response times* can easily be avoided and more realistic dynamic characteristics can be obtained for LCD-monitors and LCD-TVs. A second improved method is also outlined.

1 Introduction

The temporal response of the luminance of LCD-monitors to changes of the input signal is usually characterized by the time period (t_{90}-t_{10}) that elapses between a change of 10% and 90% with respect to the final constant luminance states (0%, 100%) as illustrated in fig. 1. When the backlight employs pulse-width modulation (PWM) for dimming of the intensity it is sometimes complicated and more often impossible to correctly determine the transition characteristics (*response times* t_{90}-t_{10}) since the temporal modulations of the backlight are concealing the transition of the LCD as illustrated in Fig. 2.

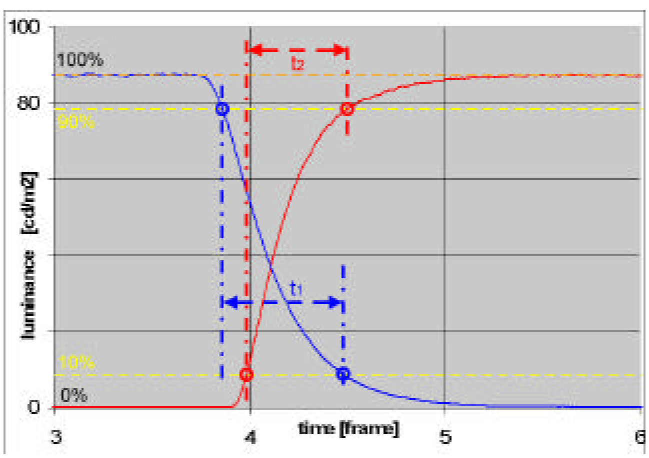


Figure 1: Luminance versus time showing two well conditioned monotonous transitions between two optical states without parasitic fluctuations or modulations, overshoot or undershoot.

It is common practice in display metrology [1, 2, 3, 4] to remove such parasitic periodic modulations by *moving-window averaging*, a process also called *convolution*. Depending on the details of the luminance versus time function, the periodic modulations can be removed in a more or less satisfactory way.

Due to averaging however, the transition from the first luminance level to the second is slowed-down and the response times (t_{90}-t_{10}) now obtained are longer than the actual transitions of the LCD. This effect becomes more severe with decreasing transition times of the LCD (switching accelerated by *overdriving* methods) and decreasing fundamental frequency of the modulations of the backlight luminance (e.g. 100Hz).

2 Modeling of transitions

We have measured the luminance as a function of time for a range of state-of-the-art LCD-monitors for 5 start and finish gray levels respectively (0%, 25%, 50%, 75% and 100%) with the optical transient recorder OTR-3 [5, 6].

The recorded luminance functions are analyzed with respect to their spectral content in order to identify and eventually separate the following components:

- LCD transition following the input signal (~1Hz), $\tau(t)$,
- backlight modulations (100Hz – 300Hz), fundamental and harmonics, b(t),
- frame-response (refresh) modulations (60Hz – 75Hz),
- others (e.g. noise), $\nu(t)$.

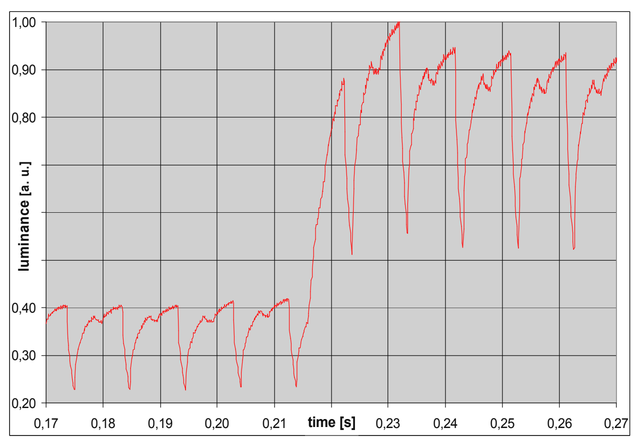


Figure 2: Luminance vs time (measurement) showing strong modulations induced by the PWM circuit of the backlight unit.

We thus approximate the measured luminance vs. time function y(t) as product of backlight intensity b(t) and LCD transition $\tau(t)$:

$$y(t) = b(t) \cdot \tau(t) \tag{1}$$

From the fundamental frequency component of the backlight modulation, f_d, we determine the width for the averaging window, $T_{MA}=1/f_d$ and perform the convolution. The plateau levels are then obtained from the resulting function (the yellow curve in fig. 3) via histogram analysis or by averaging over regions of that curve that are sufficiently flat. The convolution process removes the modulations caused by the backlight, but also makes the transition $\tau(t)$ less steep than it actually should be, since f_d and its harmonics are removed from y(t).

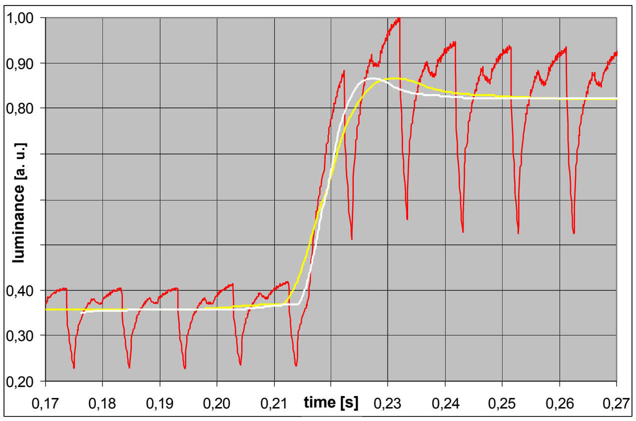


Figure 3: The yellow curve is obtained via convolution with a rectangular window of width $T_{MA}=1/f_d$ (f_d=fundamental frequency component of the backlight modulation, here 104.2 Hz=1/9.6ms). The slope of the transition of the yellow curve is slowed-down due to the convolution process. The white curve shows the transition corrected by deconvolution according to the procedure described below and then rescaled in time.

In order to correct for that unwanted effect of convolution on the transition $\tau(t)$ we have modeled the transition from a first constant state to a second by two sigmoid functions (a cumulative Gaussian distribution and a logistic function) and by a linear transition as show in figs. 4. These functions have been normalized and adjusted to the same initial flatness of $(t_{90}\text{-}t_{10})$=0.8.

We have computed the change of the steepness of the transition in terms of $(t_{90}\text{-}t_{10})$ for a range of convolution window widths, T_{MA}= 0.5, 1, 1.5, 2, 3, 4) as illustrated in fig.5. With increasing T_{MA} the ratio of convolution window to slope width, $T_{MA}/(t_{90}\text{-}t_{10})^*$ approaches a limiting value of 1/0.8 = 1.25. This is equivalent to convoluting an ideal step function with a window of width 1.

The variation of the factor about which the steepness of the slope of the transition is decreased (i.e. the value of $(t_{90}\text{-}t_{10})$ is increased) is quite independent of the nature of the function chosen for modeling of the transition between two states as illustrated in figs. 4. The following results are based on the modeling of the transition with the logistic function.

The factor f_C about which the steepness is reduced by convolution is given by

$$f_C = \frac{(t_{90} - t_{10})}{(t_{90} - t_{10})^*} \tag{2}$$

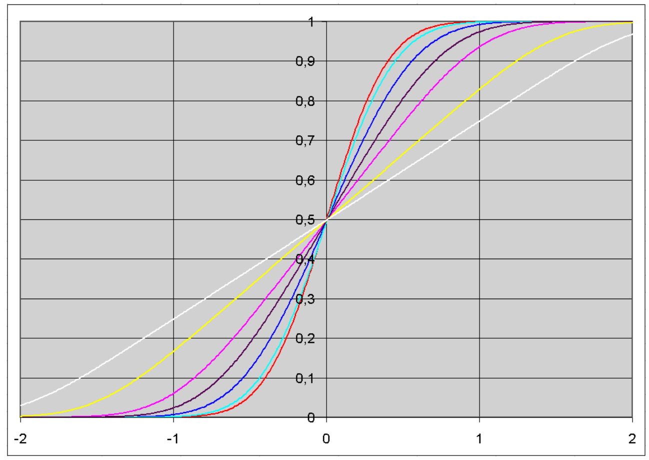


Fig. 4A: Cumulative Gaussian distribution function

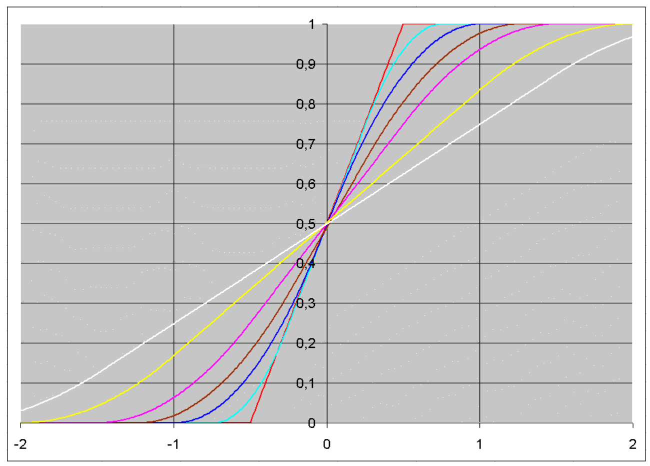


Fig. 4B: Linear transition

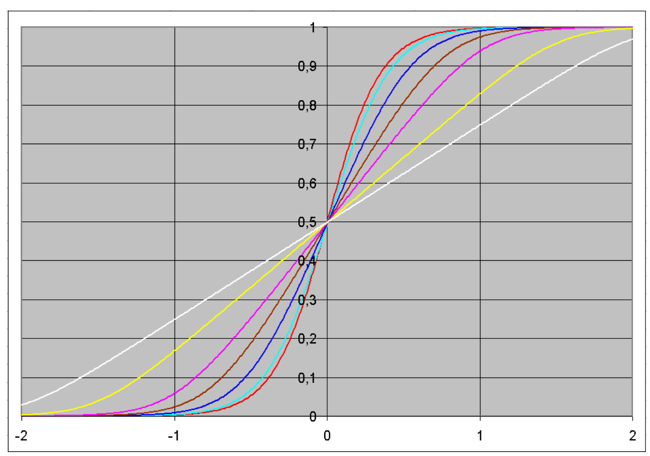


Fig 4C: Logistic function

Fig. 4: Three sigmoid functions (red curves) used for *modeling of* the temporal transition between two constant optical states (here: stationary gray levels). All initial curves are adjusted to the same flatness $(t_{90}\text{-}t_{10})$=0.8. The other curves with decreasing steepness are resulting from convolution with rectangular windows of widths T_{MA} = 0.5, 1, 1.5, 2, 3, and 4 (white curves).

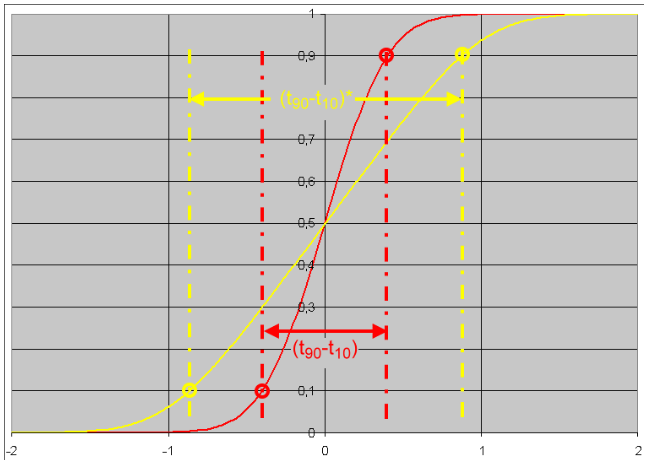


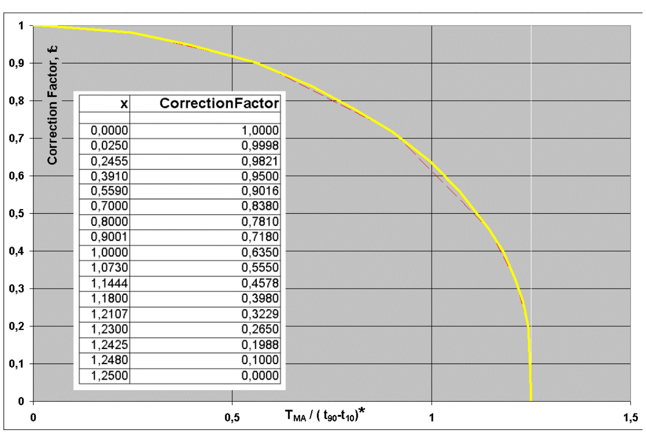
Figure 5: The red curve represents an ideal original transition as measured, before any numerical treatment (e.g. convolution), its slope specified by the flatness (=1/steepness) (t_{90}–t_{10}). After convolution (i.e. *moving window averaging*), the yellow curve is obtained featuring an increased flatness (i.e. reduced steepness), specified by the parameter (t_{90}–t_{10})*.

This factor is a function of the width of the convolution window, T_{MA}, related to the unknown flatness of the original transition, (t_{90}–t_{10}):

$$f_C = \frac{(t_{90} - t_{10})}{(t_{90} - t_{10})^*} = g\left(\frac{T_{MA}}{(t_{90} - t_{10})}\right) = f\left(\frac{T_{MA}}{(t_{90} - t_{10})^*}\right) \tag{3}$$

Starting with a sigmoid curve with known flatness of figs.4, we have calculated the flatness of the transitions, (t_{90}–t_{10})* after convolution with windows of width T_{MA} (fig. 5) and evaluated the correction factor f_C=f((t_{90}–t_{10})*) as shown in fig. 6.

When the steepness of the original transition 1/(t_{90}–t_{10}) approaches infinity (i.e. T_{MA} >> (t_{90}–t_{10})) as is the case for step transitions where (t_{90}–t_{10})*=0.8), the correction factor f_C goes to zero.



x	CorrectionFactor
0,0000	1,0000
0,0250	0,9998
0,2455	0,9821
0,3910	0,9500
0,5590	0,9016
0,7000	0,8380
0,8000	0,7810
0,9001	0,7180
1,0000	0,6350
1,0730	0,5550
1,1444	0,4578
1,1800	0,3980
1,2107	0,3229
1,2300	0,2650
1,2425	0,1988
1,2480	0,1000
1,2500	0,0000

Figure 6: Graphical representation of the **correction factor for flatness after convolution** (t_{90}–t_{10})* as a function of T_{MA}/(t_{90}–t_{10})* with a table of values of the correction factor.

4 Extension of the Approach

The described approach is limited (1) with respect to overshoot, which is not originally considered by the model functions used for calculation of the correction factor and (2) in limiting cases when the original transition times are short compared to the convolution window (T_{MA} >> (t_{90}–t_{10})).

An extension of the presented method has recently been devised by Tobias Elze [6]. It is based on the evaluation of b(t) with subsequent determination of the transition τ(t) by division:

$$\tau(t) = \frac{y(t)}{(b(t) + \nu(t))} \tag{4}$$

under the condition that noise effects, ν(t), can be neglected.

The backlight modulation function b(t) can be obtained

- from the plateaus (t →∞) where τ(t) has settled,
- from separate measurements of the constant state.

Details of this approach, e.g. how to determine the correct phase of the function b(t) will be described in a forthcoming publication. A typical result obtained with that method from a case with pronounced backlight modulations is shown in fig. 7.

5 Specsmanship at work: Excess overdriving

In order to speed-up the transitions of LCDs the method of *overdriving* is commonly applied these days in commercial products. Evaluation of the LUTs that are the basis for overdriving requires measurement of the dynamics of various transitions, perferably as a function of LCD-panel temperature. It can be increasingly observed in LCD-monitors that overdriving is exaggerated in order to obtain fast transitions (t_{90}–t_{10}) and thus "attractive numbers" for the data-sheet. The drawback of such "overdriven" overdriving is a considerable overshoot of the optical response and a long time has to pass before the optical response finally settles to a stable state as shown in fig. 7.

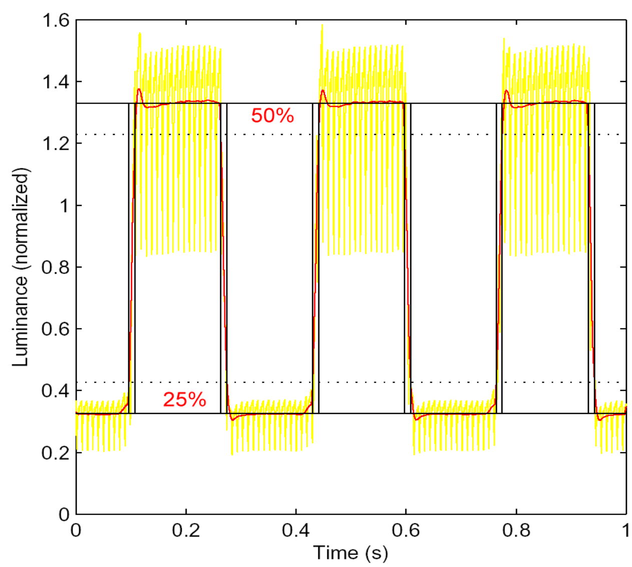


Figure 7: Transitions between gray-levels of 25% and 50% with over- and undershoot. Settling to the target luminance requires several frame periods. Evaluation of τ(t) according to the method of Tobias Elze [6].

The abuse of overdriving in order to pass the 90% level as fast as possible at the expense of overshooting can be cured effectively by additional rating of the degree of overshoot or by modification of the definition of *response times* to discourage implementation of exaggerated overshoot. We propose to introduce a maximum overshoot which is tolerated (e.g. 10%) and above that limiting value, he transition time is not specified by the 90% and 10% changes, but rather by the 110% and 10% changes and thus by the period (t_{110}–t_{10}) as illustrated in fig. 9.

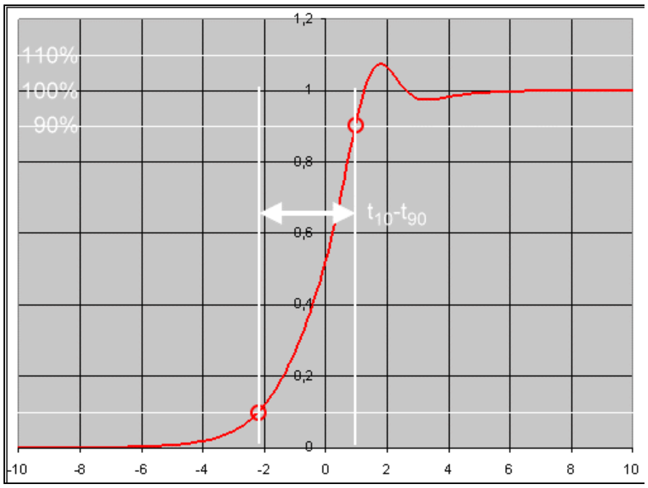


Figure 8: Transition time (t_{90}–t_{10}) for the case that the overshoot remains below 10%.

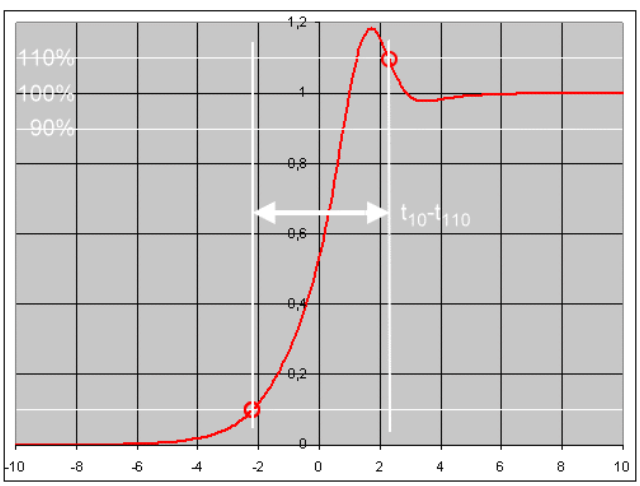


Figure 9: Prolonged transition time (t_{110}–t_{10}) for the case that the overshoot exceeds 10%.

6 Typical Result

LCD transition times (t_{90}–t_{10}) are typically in the range of 10ms (with overdriving 2ms – 20ms) and convolution windows in the range of 1ms ≤ T_{MA} ≤ 10ms (i.e. 100Hz to 1000Hz dominant frequency of backlight modulations).

We take the measurement data of the diagrams of figs.2 and 3 as a numerical example. With a 104 Hz backlight modulation and a transition period (t_{90}–t_{10})* of 9.7 ms after convolution we obtain for the ratio [T_{MA}/(t_{90}–t_{10})*] a value of 0.9897 for which we read the **correction factor** from the diagram above as **~0.63** (i.e. 6.1ms instead of 9.7ms).

For infinitely fast transitions (step functions) and when b(t) adds a steep gradient to the transition τ(t), the period (t_{90}–t_{10})* after convolution approaches $0.8 \cdot T_{MA}$ and thus [T_{MA}/(t_{90}–t_{10})*]→1.25 or beyond, depending on the phase of b(t). For values close to 1.25 it becomes increasingly difficult to accurately determine the correction factor because of the increasing steepness of the curve.

7 Discussion

The target functions used in this work do not take into account pronounced overshoot and the method is limited in the case of fast transitions combined with low-frequency backlight modulations. These limitations can be overcome by an improved method based on extraction of the transition of the LCD-panel by division [6].

8 Conclusion

We have introduced an approach for evaluation of LCD-transition periods when the measured temporal luminance response is dominated by periodic backlight modulations. The method is simple and easy to implement, but it considerably improves the accuracy of evaluation of transition times in typical practical cases and thus the data specifying LCD-dynamics. A second method that overcomes the limitations of the first approach has been outlined additionally. Both methods together are a solid basis for realistic evaluation and specification of the dynamics of LCDs.

References

[1] ISO 13406-2, 3.4.4, Image formation time: time for the relative luminance to change from 10% to 90% and back.

8 Measurements
8.7.21 Image formation time, frame period averaging

[2] ISO 9141-305

6.4 Temporal performance measurements
6.4.1 Temporal luminance variation
6.4.2 Image formation time, ripple filtering
6.4.3 Image formation time between gray-levels transitions between 5x5 or 9x9 levels of gray

[3] IEC 61747-6

5.3 Response times (turn-on time, turn-off time, rise time and fall time)

[4] Vesa FPDM-Version 2.0

303-9 Luminance step-response
305 Temporal performance
305-1 Response time

[5] OTR-3 by Display-Metrology&Systems www.display-metrology.com

[6] Tobias Elze, personal communication. The cooperation in the "LCD-dynamics" project is highly appreciated. This improved method for extraction of the LCD-transition by division will be published by Tobias Elze in a forthcoming paper together with a range of evaluation results.