26.1: Motion Blur Measurement and Evaluation: From Theory to the Laboratory

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Abstract
This paper presents and compares motion blur data of an LCD-monitor obtained with three different approaches: moving targets imaged with a stationary high-speed camera followed by numerical analysis, evaluation of step and impulse-responses measured with stationary test patters. A complete and detailed characterization of an electronic display including intended or parasitic lateral effects seems to require imaging methods and moving test-patters while the evaluation of temporal transitions between different states of electrical driving (e.g. gray-to-gray transitions) provides easily accessible motion blur data that may be sufficient for many applications and product specifications.

1 Introduction
The display of moving images on flat-panel displays is still affected by distortions and artefacts, especially when compared to CRT-based monitors and TV-sets. Measurement, evaluation and rating of these ***motion artefacts*** is urgently required for development and systematic optimization of suitable counter-measures and for objective specification of the performance of various flat-panel display technologies (i.e. LCD, PDP, etc).

1.1 Origins of motion blur
The motion-induced distortion of a visual target moving across an electronic display screen perceived as *blurring* of initially sharp edges by a human observer (*motion blur*) is caused by two effects:

1. by the ***hold-type*** characteristics of the electro-optical response of the display (*impulse-type displays* do not cause motion blur) and
2. by ***integration*** of the human visual system while smoothly following the movement of the target (i.e. *smooth pursuit* or *eye-tracking*).

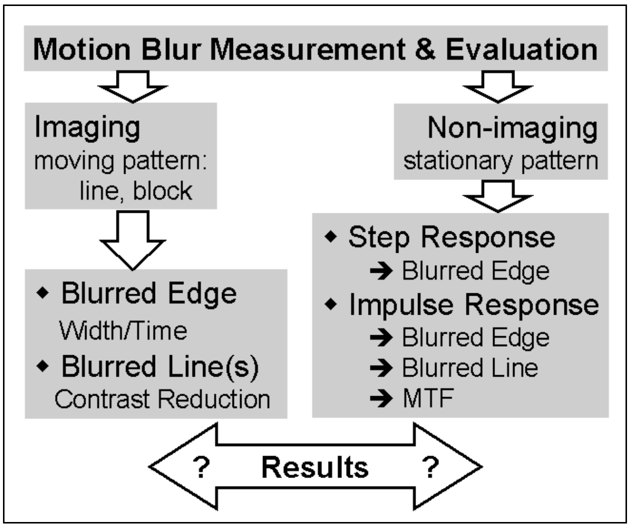
The increased response times of LCDs (e.g. compared to CRTs), especially when switching between intermediate levels of gray, corrupt the visual quality of moving objects and thus contribute to motion blur, but they are not the actual cause.

The method of *eye-trace integration*, the basis for evaluation of motion blur, after its introduction by Kurita [1], has been discussed in detail in a series of papers by Sekiya [e.g. 2].

1.2 Measurement and evaluation of motion blur
Data for evaluation of motion-blur can be acquired in four ways with two kinds of test-patterns and two classes of detectors:

- **moving patterns** (movement of a visual target recorded with a tracking [3] or stationary [4] camera),
  - **block-pattern**, wide enough to allow settlement of the optical response to a stationary state) and
  - **line-pattern** (e.g. one pixel wide),
- **stationary patterns** (intensity vs. time measured with a spot-meter with fixed location of the spot of measurement),
  - **step-response** (optical response settles to stationary state, [5]), and
  - **impulse-response** (test-pattern active for one frame period, [5]).

A direct reproduction of the tracking of a visual target by a human observer is attempted by the class of “pursuit camera systems” where the field-of-view of the camera is put into motion by a moving mirror (e.g. galvanometer scanner, rotating polygon mirror) or by a linear motion device.



When the camera is stationary, the movement of the visual target can be recorded by many individual images taken during one frame period of the display followed by numerical processing of the images to realize a pursuit of the target and evaluation of the corresponding blur characteristics.

A second category of approaches for measurement and evaluation of motion blur effects is based on the theoretical analysis of temporal and spatial apertures of display devices [5, 6]. It can be shown, that, under certain conditions, motion blur effects can be evaluated from the impulse response or from the step-response of the display under test without moving test patterns [5, 6, 7, 8].

2 Experimental
In our experiments we have used 3 of the 4 measurement approaches listed above as realized by the following instruments:

- **MADRAS**, a motion-blur-analyzer system based on a stationary high-speed camera and an evaluation software package [9],
- **OTR-3**, an optical transient recorder for measurement of temporal luminance variations [10].

Measurements have been carried out at four gray-levels RGB=0/91/139/255 with an LCD-monitor of the normally-black type (IPS) as display under test (DUT).

2.1 Stationary camera with image-processing
This approach can be used with two kinds of test-patterns

depending on the objective of the evaluation (blurred-edge width (BEW) or line-spreading and related contrast degradation):

When a moving block target is used as test-pattern, the block-width, w, should be several times the advancement (step-width) per frame, Δ (e.g. w=5·Δ) in order to allow the optical response to settle to a steady state which then serves as reference level for the evaluations (100% or 0% level). This timing reproduces the step-response of the display under test. It must be assured that the optical response of the display under test (DUT) is sampled with a sufficient number of images per frame-period. We have used exposure periods of 1 ms duration for all measurements. The maximum angle of inclination at the boundaries of the camera image in the setup used was 8°.

Construction of the intensity-profile projected on the retina of the observer under the conditions of smooth visual pursuit of the target follows the procedures described by Sekiya [2].

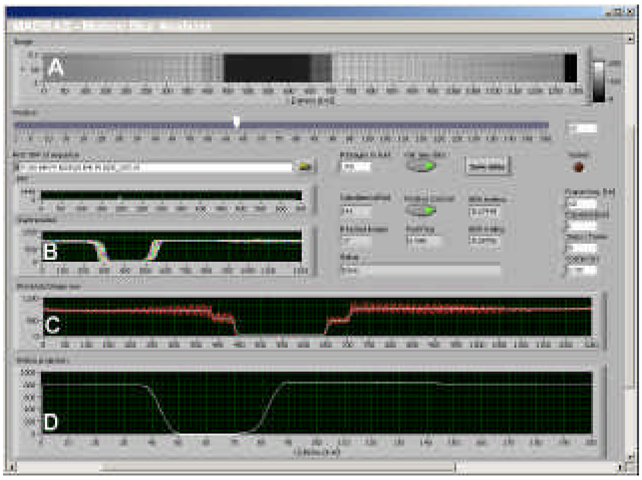


Figure 1: Screenshot of the GUI of the MADRAS motion-blur-analyzer software with camera-image (A), intensity profiles re-arranged along the motion trajectory (B), intensity profile of the actual camera-image (C), intensity profile on the retina (D).

Characteristics for the width of the blurred edges can be obtained e.g. by the distance between the 10% and 90% luminance levels (BEW) for both rising and falling edge. The optical transitions should be classified according to the underlying electrical driving conditions (i.e. increasing or decreasing voltage, ON and OFF respectively) rather than by the slope of the optical response to avoid confusion (a normally-black VA-LCD is activated to turn bright, a normally white TN-LCD is activated to turn dark). As a consequence of such asymmetrical transitions of LCDs (field-induced and relaxation) the blur-characteristics for both edges (rising, falling) are usually different from each other.

A line-target of width of one pixel advancing at a speed Δ≥1 pixel per frame (or of a block target with Δ>>w) reproduces the impulse response of the display under test. Depending on the dynamics of the LCD and the speed of the movement, the line appears to be spreading and losing contrast [11]. Especially the reduction of contrast is quite sensitive with respect to the speed of transitions of the DUT and thus a useful experimental probe.

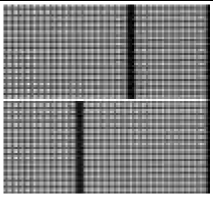


Figure 2: Camera-images of a dark line-target advancing on a light background (RGB=0/255, pixel matrix visible) by 8 pixels per frame (60 Hz frame frequency), exposure time T_{exp} = 1ms. Two positions of the line are shown with a time-difference of 17 ms.

2.2 Measurements with stationary patterns at fixed locations

2.2.1 Step-response

The NBET is obtained from the step-response by convolution with a window of the width of one frame-period [5, 6, 7]. We obtain separate NBETs for both rising and falling edge and thus separate characteristics for the *field-induced-switching process* (i.e. increasing driving voltage) and for the *relaxation process* (due to restoring elastic forces in the LC) depending on the type of LCD (i.e. normally black or white).

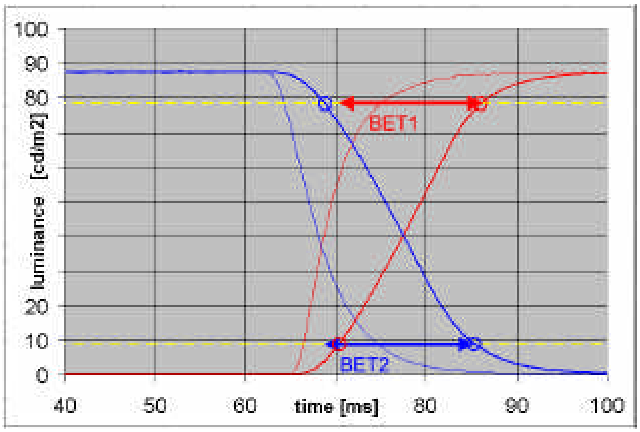


Figure 3: Step-response for transitions between RGB=0 and 255 (thin curves). Settling to the target-luminance takes longer than one frame-period (T_F = 16,667 ms). Convolution of step-response (thick lines) with a window of 1 frame-period width. BET1, BET2 are evaluated between 10% and 90% levels.

2.2.2 Impulse-response

Since the impulse-response of LCDs comprises two intensity transitions with different directions it combines a field-induced-switching process (i.e. increase of driving voltage) with a relaxation (induced by restoring elastic forces in the liquid crystal layer). In order to separate both effects, some processing of the acquired data is required. This can be achieved using an assembly-technique that brings together the field-induced and the relaxation parts from two separately measured pulses in one combined impulse. The *cross-completion* method brings together e.g. the rising-edge of the red curve of Fig. 4 with the inverted rising edge of the blue curve for formation of a combined ON-impulse. Since the change of intensity during the switching is different for both curves, an amplitude re-scaling is usually required to match both parts of the curve.

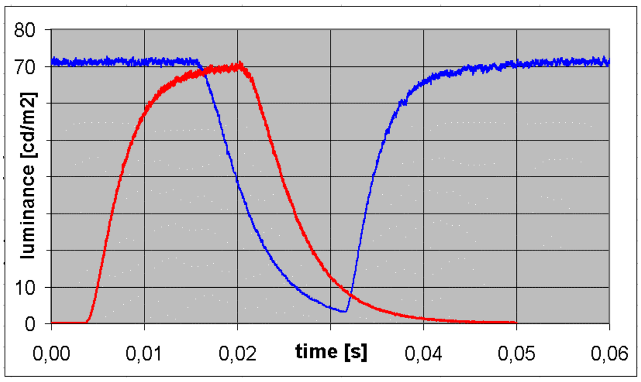


Figure 4: Impulse-response between RGB=0 and 255. The target-luminance is not reached within one frame-period effecting a reduction of contrast.

The asymmetry of the impulse-response is obvious: the transition from dark to light (red curve, increasing voltage) settles more completely within one frame period (16.667 ms) than the transition from light to dark (blue curve).

The blue-curve first shows a relaxation transition to dark, which, at the end of the frame has not reached the same change in optical response as the corresponding field-induced transition of the red curve. As a consequence, the starting condition for the field-induced switching to the bright state at the beginning of the second frame is different from that of the rising edge of the red curve. This asymmetry does not recommend the cross-completion method. The preferred assembly-method with less assumptions thus brings together e.g. the rising edge of the red curve with its own inversion serving as falling edge (*auto-completion*).

For calculation of the blurred-edge characteristics both ON and OFF-impulse have to be positive pulses with the stationary values set to zero to assure finite integrals. Two pairs of impulse-responses are thus obtained from the measured data (ON and OFF pulse for each of blue and red curve) via assembly of original and inverted edges. These pulses are then integrated and from the resulting transition the BET is determined by the time interval elapsing between a change of 10% and 90% of the stationary values.

Completion and assembly of the impulses requires the knowledge of one more detail: the moment when the LC-pixel voltage changes from one level to the next. Since this moment in time is difficult to assess, we have assumed for our evaluations that switching occurs at the moment when the luminance level has reached its maximum or a minimum value.

The procedure published by Slyuterman [12] combines both types of transitions (field-induced and relaxation) and as a consequence, these results differ from BET/BEW values obtained from moving block-targets or from step-responses, the difference increasing with the asymmetry of LC-switching.

2.2.3 Dynamical Contrast Reduction

The contrast of a moving-line pattern is evaluated by the integral of the impulse response (luminance) taken over the first frame-period (see Fig. 4). Relative values are obtained by relating this integral over the first edge of the impulse to the stationary luminance.

3 Results

Transition times, (t_{10}-t_{90}) [ms]				
finish → **start ↓**	**0**	**91**	**139**	**255**
0		19,23	16,78	7,45
91	8,44		15,80	6,69
139	9,09	15,35		6,63
255	9,80	16,23	14,75	

Table 1: Gray-to-gray step response times

NBETs from Step-Response				
finish → **start ↓**	**0**	**91**	**139**	**255**
0		1,49	1,34	0,92
91	0,94		1,29	0,90
139	0,96	1,32		0,90
255	0,99	1,32	1,32	

Table 2: NBETs from step-response measurements, VC ≈ 1%

For comparison: the NBET for the ON-pulse of fig. 4 is 0,90 (0→255) and 0,96 for the OFF-pulse (255→0).

NBET from MBA - D = 4				
finish → **start ↓**	**0**	**91**	**139**	**255**
0			1,51	1,09
91				1,04
139	1,20			
255	1,18	1,48		

Table 3: NBETs at Δ = 4 steps per frame period.

NBET from MBA - D = 8				
finish → **start ↓**	**0**	**91**	**139**	**255**
0			1,49	0,93
91				0,92
139	1,04			
255	1,06	1,41		

Table 4: NBETs at Δ = 8 steps per frame period.

NBET from MBA - D = 16				
finish → **start ↓**	**0**	**91**	**139**	**255**
0			1,43	0,98
91				0,96
139	1,09			
255	1,03	1,49		

Table 5: NBETs at Δ = 16 steps per frame period. VC~5%-10%

2.2.4 Effect of display-loading

Evaluation of the blurring of edges of moving targets from intensity variations at a fixed location on the DUT requires the independence of the dynamical properties of the DUT from image content. We have carried out measurements of the step-response between a range of gray-levels for 4 sizes of the activated area of the test-pattern (full-screen, 1/2, 1/4 and 1/8 screen). The results of this analysis does not show a systematic variation of the response times with the activated area of the test-pattern.

3.1 Verification of methods and results

1 **Reference display:** In order to verify the performance of the different methods for motion-blur measurement and analysis (especially those using image-acquisition) we have build an idealized display with a transparent and user-controllable timing using LEDs as picture elements, thus assuring fast transitions with t_{on} < 100ns. This device comprises one line of pixels of which the frame-frequency and the duty-ratio can be chosen freely. A duty-ratio of 100% represents a perfect hold-type display while a duty-ratio of ~1% represents an impulse-type display (e.g. CRT). In addition, the width of the moving target (block or line) and its speed of advancement can be programmed from a computer via USB [13].

2 **Synthetic images:** We also have synthesized images with well defined lateral and temporal intensity distributions (including black-mask structure) for evaluation and comparison with analytic evaluations, thus confirming the performance of our evaluations.

3 **Cross-comparisons:** Variation of step-response times with size of test-pattern, comparisons between step-response & moving target evaluations, comparison of luminance-vs.-time curves from camera images with OTR data to check for neighborhood effects.

4 Discussion

NBETs from the step-response can be evaluated with low uncertainties (a few %) and they were always shorter that the results obtained with moving targets. These NBETs are not independent of the speed of pattern translation, Δ, as predicted by theory. There is a good match between the NBETs from impulse and step response.

For the LCD-monitor used for our experiments we could show lateral coupling effects not included in the evaluations carried out with stationary patterns.

5 Conclusion

As a result of a variety of data-processing steps in state-of-the-art LCD-monitors, especially for TV-applications, it is impossible to predict which conditioning procedures the input signal has undergone before it is arriving at the target-pixel(s). The data-processing involved may even intentionally create or amplify lateral couplings between the individual pixels (e.g. scaling procedures, edge and sharpness enhancement, etc.).

Additionally, the electronic circuitry of active-matrix LCDs may include capacitive coupling between adjacent columns or lines of pixels and sub-pixels [see e.g. 14].

As a consequence, we cannot completely characterize the motion display characteristics of LCD-screens by evaluation of temporal luminance transitions measured at a fixed location on the screen.

BETs obtained from *step-response transitions* are easily obtained as a "spin-off product" of gray-to-gray transition measurements as required for specification of image-formation times (gray-to-gray response time, *image-formation time* see ISO 9241-305). Compared to other BEW/BET evaluation routes they represent best-case results and, for reasonably low lateral coupling effects,, seem to be valuable first-order approximations.

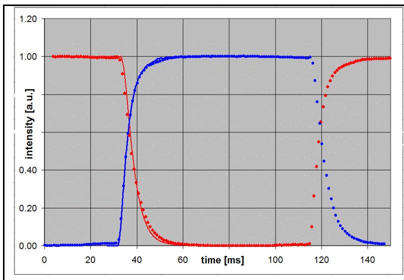


Figure 5: Normalized intensities vs. time obtained from camera measurements (dotted lines) and OTR-measurements (continuous lines). Measurement window is one step wide.

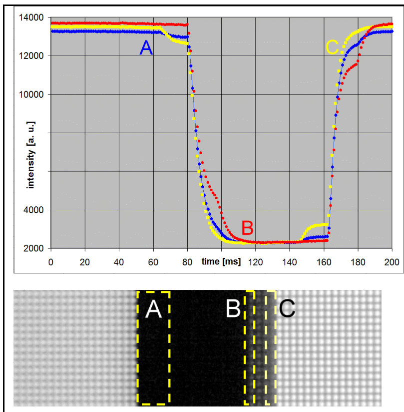


Figure 6: Intensity vs. time measured in areas of different size and at different locations. Δ = 4 pixels/frame.

Curve A corresponds to the condition of the measurement shown in fig. 5.

Location and size of measurement areas
area A is one step wide
area B is 1/3 step wide
area C is 1/3 step wide

Evaluation of *impulse-responses* to obtain the MTF, blurred-edge characteristics or motion induced contrast reductions requires data-manipulation in order to make a distinction between field-induced and elastic reorientations in the LC-layer. Evaluation of BETs from moving targets is more demanding with respect to the required instrumentation and the data-processing, but at the same time it includes and considers all artefacts that are caused by data-processing and parasitic lateral couplings in the LCD-monitor.

References

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