PREDICTING FLICKER THRESHOLDS FOR VIDEO DISPLAY TERMINALS

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Abstract—This paper describes an analytical method for *predicting* whether a video display terminal will appear to flicker given the screen phosphor persistence, refresh frequencies, and other environmental factors such as ambient light level, the distance between the viewer and the display, etc. From the method, one can predict the maximum screen luminance and the minimum refresh frequency that will generate a flicker-free display for a *theoretical standard observer*. These predictions are tested across a wide range of refresh frequencies, screen luminances, screen phosphors, and individual users.

I. BACKGROUND

Operators of video display terminals (VDTs) frequently complain of disturbing screen flicker. As a result, several standards require VDTs to be "flicker-free". Unfortunately, current VDT standards do not specify how to define or design a flicker-free display. This poses a problem for display engineers who wish to design their displays to eliminate annoying screen flicker and, consequently, meet the flicker-free requirements of VDT standards. It would, therefore, be of great value to have a method for determining whether a particular display appears to flicker.

Various methods have been proposed for empirically determining whether a particular VDT will appear to flicker under specified environmental conditions. Although empirical evaluations can provide a very thorough analysis of the perceived flicker properties of a display, the methods take a considerable amount of time and training. In some instances, an analytical method for approximating or predicting the flicker properties of a display is desired.

Furthermore, empirical methods have a number of disadvantages that limit their utility. First, they are inherently limited by the fact that the methods require a physical prototype of the display. One cannot, for example, empirically evaluate an imagined or theoretical design of a display that has not been implemented. Second, although empirical methods of screen flicker evaluation can indicate whether a particular display appears to flicker, they are not able to specify what design changes will result in a flicker-free display. Finally, the empirical methods require displays engineers to conduct experiments that are both difficult to perform and difficult to verify.

In this paper we describe an analytical method that can be used during the *design phase* of a display to select the display parameters that will result in a flicker-free display. The method is based on a model of how sensitive people are to temporally-varying lights.

Research on human flicker sensitivity (Ives, 1922; DeLange, 1961; Kelly, 1961, 1969, 1971) indicates that when a temporally varying light is decomposed into component temporal sine waves, flicker sensitivity can be predicted by the amount of stimulus energy in the lowest or fundamental temporal frequency. Based on this research, it is possible to define a *standard observer* that detects "flicker" if the stimulus energy in the fundamental frequency of any time-varying light is greater than a predetermined threshold value that depends on the particular frequency. Stimulus energy is specified as the absolute amplitude of the fundamental temporal frequency in units of retinal illuminance and there is a single formula that predicts the threshold amplitude of the fundamental temporal frequency that will be detected by a "normal" or "standard" observer viewing a flickering light at a standard viewing distance under a wide range of room illuminations (Ives, 1922; Kelly, 1961, 1969, 1971). This previous research on human flicker sensitivity forms the basis of our method for predicting screen flicker.

II. A METHOD FOR PREDICTING SCREEN FLICKER

The proposed method for predicting screen flicker is based on a Fourier decomposition of the time-varying screen luminance. The Fourier analysis of the time-varying screen luminance is simplified by the fact that the fundamental temporal frequency of a VDT is equal to the refresh frequency. If one knows the absolute amplitude of the fundamental frequency in the Fourier series describing the temporally modulated screen luminance, then one can predict whether the screen will appear to flicker.

From previous research (Kelly, 1969, 1971; Tyler & Hamer, 1987), it is predicted that if the absolute amplitude of the fundamental temporal frequency of the display luminance modulation is greater than a pre-determined frequency-dependent threshold value, E(f), then observers will perceive flicker.

$$E(f) = ae^{bf}, \tag{1}$$

where f is the refresh frequency and a and b are constants that depend on the size of the display.[1]

Knowing the absolute amplitude of the fundamental temporal frequency of the display, $E(f)_{obs}$ one can carry out the following tests:

If $E(f) > E(f)_{obs}$, then the prediction is that people will not see flicker.

[1] Equation (1) is a simplified version of Kelly's (1969) original flicker regression equation implemented as a flicker metric by Farrell (1986, 1987a). Tyler & Hamer (1987) have shown that Eq. (1) generates identical predictions as Kelly's original equation for the stimulus conditions with which we are concerned. This finding is supported by our results as well.

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If $E(f) < E(f)_{obs}$, then the prediction is that people will see flicker.

Conversely, one can predict the critical flicker frequency (CFF), i.e., the lowest refresh frequency that will render a display "flicker-free',

$$CFF = \frac{\ln[E(f)_{obs}] - \ln(a)}{b}$$

or

$$CFF = m + n\left\{\ln[E(f)_{obs}]\right\} \qquad (2)$$

where

$$m = -\left(\ln \frac{(a)}{b}\right) \quad \text{and} \quad n = \frac{1}{b}.$$

The method for predicting screen flicker is, then, reduced to the problem of calculating the absolute amplitude of the fundamental frequency of the temporally varying screen luminance. The procedure for this calculation is outlined in Appendix I.

Appendix I also describes how phosphor persistence influences the absolute amplitude the fundamental temporal frequency. For example, for a fixed refresh rate, displays with long phosphor persistence (e.g., P39 phosphor) need to be made brighter than displays with short phosphor persistence (e.g., P4), in order to obtain the same amplitude of the fundamental temporal frequency. But, having taken the phosphor persistence into account, the flicker thresholds for short and long phosphor displays should be the same. In other words, for both short and long phosphor displays, the probability of seeing flicker should depend only on the absolute amplitude of the fundamental temporal frequency.

Previous studies (Ives, 1922; Kelly, 1961, 1969, 1971; Farrell, 1986, 1987a; Tyler & Hamer, 1987) have established that there is a single and general equation predicting the critical flicker frequency (CFF) and the absolute amplitude of the fundamental temporal frequency (expressed as $E(f)_{obs}$ [see Eq. (2)]. Farrell (1986) extended this finding to the evaluation of screen flicker and showed that a single curve predicts flicker thresholds for displays with different phosphor persistence, refresh frequencies and screen luminances.

III. TESTING THE ANALYTICAL METHOD

Several experiments were conducted in order to measure the variability of flicker thresholds across different users. The data were used to derive estimates of the linear regression parameters [Eq. (2)] for a large population of VDT users. These parameter estimates can then be used to define a metric for VDT flicker.

In selecting the display conditions and the observers for a flicker metric, several important facts must be kept in mind. First, flicker thresholds vary as a function of age: young people are more sensitive to flicker. Second, flicker thresholds vary as a function of display size: the larger the display, the more sensitive people are to flicker.

We chose a CRT display that, when viewed from a distance of 12 in., subtended a visual angle of 30 deg. This display would be comparable to a display, 14 in. in diameter, viewed at the normal viewing distance of 24 in. The display was modified to allow for variable refresh rates in a non-interlaced mode and was equipped with a P4 phosphor. The P4 phosphor was selected because it has a relatively short persistence (decaying to 10% of its maximum brightness in approximately 60 μsec). The short persistence allowed us to collect flicker thresholds for a wide range of screen luminances and refresh frequencies. The room illumination, measured at the surface of the display, was approximately 250 lux.

Our subject population consisted of 20 "young and rested observers" (see the ANSI VDT Standard[2]) between the ages of 23 and 39. The distribution of flicker thresholds across 20 observers is used to estimate flicker thresholds for 90% of the user population. The 90% criterion reflects the ANSI requirement that VDTs "should be flicker-free for at least 90% of a sample of the user population under conditions representative of actual use".

For several fixed luminance values (50, 100, and 150 cd/m^2), flicker thresholds were estimated by asking subjects to increase the refresh frequency of the display until they first saw flicker (ascending flicker thresholds) and then decrease the refresh frequency until they no longer perceived flicker (descending flicker thresholds). The subjects were asked to report whether they perceived flicker in any portion of the screen as they moved their eyes about the screen. For example, if subjects observed flicker in the periphery of their visual field, they were told to report that they saw flicker. The only constraint on subjects' eye movements was that they fixate their eyes on some portion of the illuminated screen. Subjects were instructed that fixating on an inactive region of the screen (such as the display bezel) would not be valid but fixating at one corner of the active region of the screen would be valid. In fact, subjects were encouraged to fixate each of the corners of the active region of the display and determine whether in any instance they could detect flicker.

For each subject, the critical flicker frequency (CFF) was estimated by the average of ascending and descending flicker thresholds. The corresponding screen luminance was used, together with the phosphor persistence time constant and the CFF, to determine the stimulus energy (i.e., absolute amplitude) in the fundamental temporal frequency of the display (see Appendix I).

Flicker thresholds were also estimated for refresh rates ranging between 54 and 70 Hz. Subjects were asked to decrease screen luminance until perceived flicker disappeared and then to increase screen luminance until perceived flicker reappeared. Again, the average of the two luminance thresholds was used, together with the refresh rate and phosphor time constant, to determine the absolute

[2] A draft of the ANSI VDT Standard can be obtained by writing to The Human Factors Society, Box 1369, Santa Monica, California 90406, USA, or by calling USA (213) 394-1811.

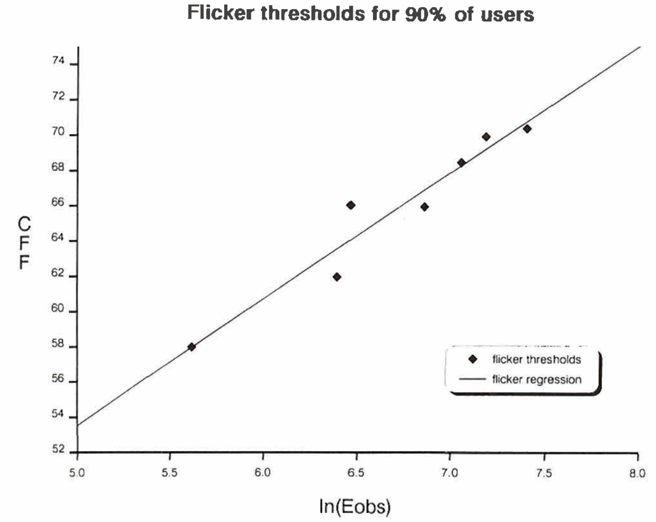

FIG. 1. Critical flicker frequency (CFF) in Hz estimated 90% of the user population plotted as a function of the natural logarithm of the absolute amplitude of the fundamental temporal frequency specified in units of retinal illuminance (trolands).

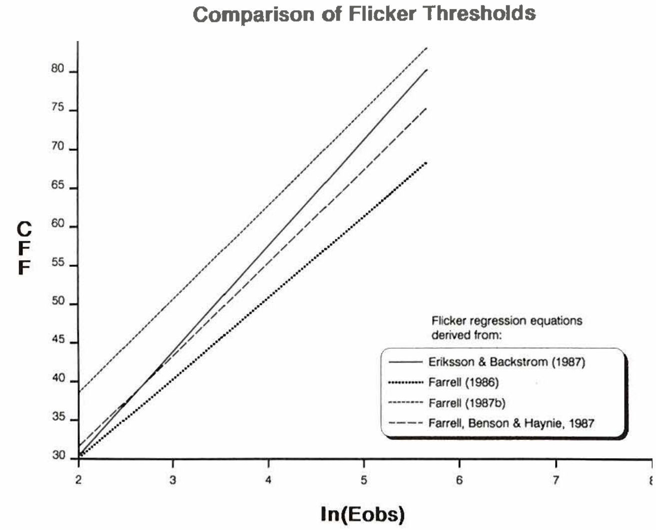

FIG. 2. Flicker regression equations derived from data reported in Eriksson & Backstrom (1987), Farrell (1986, 1987a), and in this study (Farrell, Benson and Haynie, 1987).

amplitude of the fundamental temporal frequency of the display.

Figure 1 shows the CFF estimated for 90% of the user population plotted as a function of the natural logarithm of the absolute amplitude of the fundamental temporal frequency of the display. The CFFs were derived from the mean and standard deviation of flicker thresholds obtained from the 20 observers who participated in this study. The line passing through the data points represents the best-fitting regression equation [Eq. (2)] and accounts for 93.3% of the variance in the data.

Figure 2 compares several CFF regression equations derived from data reported by Eriksson & Backstrom (1987)[3] and by Farrell (1986, 1987b). The mean and standard deviation of flicker thresholds across relatively young observers reported in these three independent investigations were used to estimate the CFFs for 90% of the user population. Flicker regression curves were then fit to the 90% CFF data.

Table I lists the parameters of the regression equations plotted in Fig. 2 along with the percent variance accounted for (R^2). In all cases, the regression equations accounted for over 90% of the variance in the data. The parameters of the CFF equations are remarkably similar despite differences in experimental methodology and subject population. This similarity suggests that it is possible to reliably predict the flicker-free display requirements for 90% of the user population.

To date, there is no simple way to predict how the parameters for the flicker regression equations vary as a function of display size. For the present time, therefore,

[3]The flicker regression equations derived from the data reported by Eriksson & Backstrom (1987) were based on flicker thresholds for screen luminances of 25, 50, 100, and 200 cd/m^2. We did not use flicker thresholds reported for screen luminances of 400 cd/m^2 because we felt that a VDT would never be viewed at luminances as great as 400 cd/m^2.

TABLE I. Flicker parameters derived from different data sets (display size subtends 30 degrees of visual angle).

$CFF = m + n[\ln(E(f)_{obs})]$

Data Set	Parameter m	Parameter n	R^2	N subjects
Eriksson & Backstrom (1987)	13.85	8.31	0.998	12
Farrell, Benson & Haynie (present study)	17.2838	7.25	0.933	20
Farrell (1987b)	24.27	7.33	0.984	10
Farrell (1986)	17.7696	6.3037	0.933	6

TABLE II. Flicker parameters for different display sizes.

$CFF = m + n\{\ln[E(f)_{obs}]\}$

Display Size (degrees of visual angle)	Parameter m	Parameter n	R^2
10	14.6	7.00	0.998
30	13.85	8.31	0.998
50	8.32	9.73	0.977
70	6.79	10.03	0.991

one must derive the parameters from the data available for displays of various size.

Table II lists the results of a linear regression analysis of data reported by Eriksson & Backstrom (1987) for displays of different sizes. (Again, we derived flicker regression equations from Eriksson & Backstrom's data on flicker thresholds for screen luminances of 25, 50, 100, and 200 cd/m^2.)

In Table II, display size is specified in degrees of visual angle:

$$\text{Display size (degrees of visual angle)} = 2\left[\tan^{-1}\left(\frac{D/2}{V}\right)\right],$$

where D is the diameter of the display (specified in millimeters) and V ≐ 500 mm, corresponding to the recommended viewing distance. Note that the diameter of the active area of a typical VDT display ranges between 10 and 12 in. Therefore, the size (in degrees of visual angle) of a typical VDT display ranges between 28 and 34 degrees of visual angle. Figure 2 provides a good summary of the main conclusions of this paper. It shows that the CFF predictions derived from four different data sets are remarkably similar. This result indicates that it is possible to predict whether any particular display will appear to be flicker-free to 90% of a young user population simply by knowing the stimulus energy (i.e., absolute energy) in the fundamental temporal frequency of the temporally varying screen luminance. The flicker-free predictions will vary as a function of display phosphor persistence (see Appendix I), refresh frequency, luminance, and display size (see Table II).

IV. APPLICATIONS OF THE METHOD FOR PREDICTING SCREEN FLICKER

The main advantage of the analytical method of screen flicker assessment is that it can be used as an evaluation tool during the design phase of a VDT. The method will allow one to deduce how variations in the display parameters will increase or decrease the probability of seeing flicker, as well as provide a means for evaluating tradeoffs in the design of flicker-free displays. For example, the method can be used to determine the display parameters, such as screen phosphor, refresh rate, screen size, and luminance, that will generate a flicker-free display. Figure 3 shows how the flicker-free refresh frequency, referred to as CFF, decreases with the time constant of the phosphor persistence and with the luminance of a display. Note that the predictions plotted in Fig. 3 are derived for a display that subtends 30 degrees of visual angle and reflects 10 cd/m^2 of the ambient light. The predictions will differ for displays varying in size.

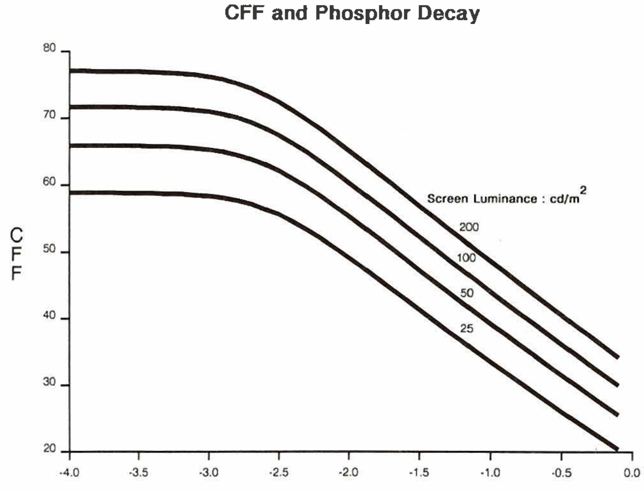

FIG. 3. Critical flicker frequency (CFF) in Hz plotted as a function of the $\log_{10}$ of the phosphor decay time constant, α [see Appendix I: Eq. (2)], with screen luminance as a parameter.

Finally, the analytical method of flicker assessment should be applicable to any type of visual display, whether it be a LCD, an electroluminescent display, or a CRT display. Although we have not explicitly tested this assumption, this generality is a consequence of two important facts. First, the temporal variation of any stimulus can be described as a sum of temporal sine waves. Second, one can predict human flicker sensitivity simply by knowing the amplitude of the fundamental temporal frequency of any time-varying visual stimulus.

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APPENDIX I: Calculating the Absolute Amplitude of the Fundamental Temporal Frequency of a VDT.

1. Convert the screen luminance into units of Trolands.
   (1) Measure the mean screen luminance over time. L_T in units of candelas per square meter (cd/m^2) using a time-integrated photometer. L_T is the total amount of light generated from the screen and it includes the amount of light reflected from the screen as well as the amount of light emitted by the display phosphors.
   (2) Turn the display off and measure the amount of light reflected from the screen, L_R, again in units of cd/m^2.

(3) Estimate the area of the observer's pupil, A, as a function of the amount of light entering the eye. Use the formula below (from Crawford, 1936) to estimate the diameter of the pupil.

$$d = 5 - 3\tanh[0.4\log(L_T 3.183)].$$

Then, pupil area is calculated as

$$A = \pi(d/2)^2.$$

(4) The DC component of the temporally varying screen luminance (specified in trolands) is

$$DC = (L_T - L_R)A.$$

II. The screen luminance is a series of pulses with exponentially decaying persistence, $e^{-[t/\alpha]}$. Compute the amplitude coefficient of the fundamental frequency of the time-varying screen luminance (see Oppenhein & Willsky, 1983):

$$\mathrm{Amp}(f) = \frac{2}{[1 + (\alpha 2\pi f)^2]^{1/2}}, \tag{2}$$

where α is the time constant of the exponential describing the phosphor persistence and f is the refresh frequency of the display.

III. The luminance modulation of the fundamental frequency, E_{obs}, is obtained by multiplying the DC component of the temporal screen variation by the amplitude coefficient of the fundamental frequency, Amp(f):

$$E_{obs} = (DC)[\mathrm{Amp}(f)]$$

The Effect of Screen Phosphor

The absolute amplitude of the fundamental temporal frequency of the display, E_{obs}, is the product of the amplitude coefficient of the fundamental temporal frequency, Amp(f), and the DC component of the temporally varying screen luminance (specified in trolands).

Fast phosphors have small decay constants. Notice that as the decay constant, α, decreases, the amplitude coefficient approaches 2. Therefore, the amplitude of the fundamental temporal frequency of a fast phosphor display will simply be twice the time-integrating screen luminance (specified in trolands). It is well known that a periodic train of pulses (generated by a very fast phosphor display) has a fundamental sine wave at a flash (refresh) frequency that is 200% modulated. Therefore, the amplitude coefficient should approach 2 as the decay constant, α, approaches zero.

A display with a very fast phosphor will, therefore, have a relatively large amplitude coefficient (approaching 2 in the maximum) and require less energy or screen luminance to be seen. This is in fact what we observe. Displays with fast phosphors (and, consequently, short decay constants) appear to flicker at low luminances. The screen luminance for perceived flicker is proportional to the decay constant of the phosphor. Since this tradeoff is incorporated in the calculation of the amplitude [see Eq. (2)], displays with different phosphors should have the same amplitude thresholds. This prediction is true only if flicker thresholds are determined solely by the stimulus energy in the fundamental frequency of the temporally modulated screen luminance, as the vision literature suggests.