ASSIST *recommends...*

Flicker Parameters for Reducing Stroboscopic Effects from Solid-state Lighting Systems

Volume 11, Issue 1
May 2012

A publication of the Alliance for Solid-State Illumination Systems and Technologies

Lighting Research Center

Rensselaer

Published by the Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union St., Troy, NY 12180, USA. Online at http://www.lrc.rpi.edu.

This publication can be cited in the following manner:

> Alliance for Solid-State Illumination Systems and Technologies (ASSIST). 2012. *ASSIST recommends… Flicker Parameters for Reducing Stroboscopic Effects from Solid-state Lighting Systems*. Vol. 11, Iss. 1. Troy, N.Y.: Lighting Research Center. Internet: http://www.lrc.rpi.edu/programs/solidstate/assist/recommends/flicker.asp.

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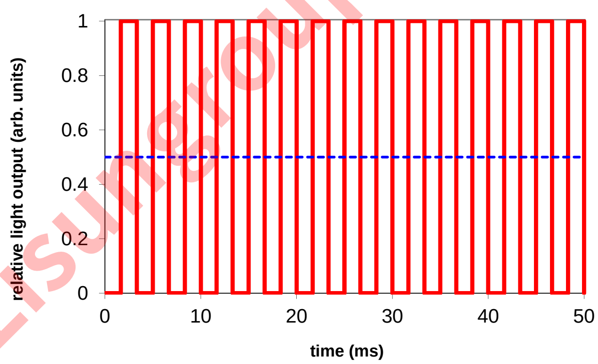
Introduction

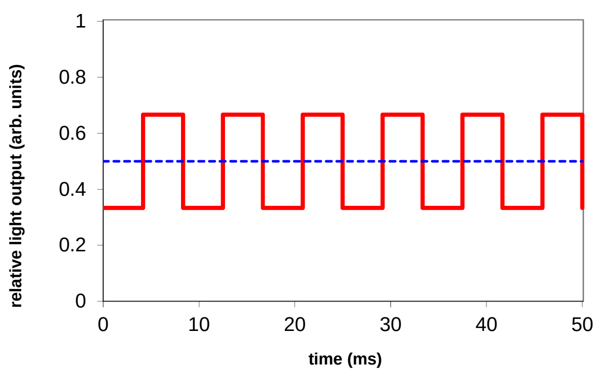
Nearly all lighting systems produce flicker, defined in this *ASSIST recommends* as the rapid fluctuation of light output in a cyclical manner. For many conventional lighting technologies (e.g., incandescent, fluorescent, and high intensity discharge [HID] lamps), flicker is a consequence of 60 Hz (largely in the Americas) and 50 Hz (in Europe, Asia, Africa and Australia) alternating current (AC) power line frequencies. Alternating polarity at these frequencies can result in flicker at twice the power line frequency (e.g., 120 Hz or 100 Hz), if electronic ballast circuitry is not employed. The thermal mass of incandescent filaments and decay characteristics of phosphors can reduce the flicker amplitude. This amplitude can be characterized in different ways (Rea 2000), the most commonly used of which are *percent flicker* and *flicker index*. Percent flicker is defined in terms of the difference between the minimum and maximum light output during a flicker waveform cycle:

$$\text{Percent flicker} = [(\text{maximum} - \text{minimum})/(\text{maximum} + \text{minimum})] \times 100\%$$

Figure 1 illustrates two rectangular waveforms showing the temporal modulation of light output as a function of time. The waveform in Figure 1a shows 100% flicker at 300 Hz, while the waveform in Figure 1b shows 33% flicker at 120 Hz.



a.



b.

Figure 1. a) Flicker waveform showing 100% flicker at a frequency of 300 Hz; b) flicker waveform showing 33% flicker at a frequency of 120 Hz.

If a light source ever produces no light during any portion of the cycle (as in Figure 1a), the percent flicker is 100%. Flicker index (Eastman and Campbell 1952) is defined with respect to a plot of the light output curve as a function of time (Rea 2000). Flicker index is the area under the light output curve and above the time-averaged light output for the entire cycle, divided by the total area under the light output curve. For a given waveform shape and duty cycle (duty cycle is defined here as the percentage of time during a flicker cycle that the light output exceeds 10% of the maximum value), percent flicker and flicker index are proportional to each other.

Direct visual perception of flicker is negligible at frequencies of 100 Hz or higher (Kelly 1961, De Lange 1958, Bullough et al. 2011). However, indirect perception of flicker is possible through stroboscopic effects at frequencies of 100–120 Hz (Rea and Ouellette 1988) and widespread perception of stroboscopic effects has been reported at 500 Hz (Hershberger et al. 1998). The variety of methods by which light-emitting diodes (LEDs) can be driven means that various flicker frequencies and percent flicker values could be possible in lighting systems using these sources. Perception of stroboscopic effects decreases as frequency increases (Hershberger et al. 1998, Bullough et al. 2011) and as percent flicker (or flicker index) decreases (Rea and Ouellette 1988). This *ASSIST recommends* document outlines a preliminary method for trading off these two factors based on recent data (Bullough et al. in press). This method does not include non-visual effects of flicker such as eyestrain or headaches (IEEE 2010).

Detection of Stroboscopic Effects

For rectangular waveforms operated so that the maximum light output is produced 50% of the time and the minimum light output is produced 50% of the time, the percent likelihood of detection (d, in percent) of stroboscopic effects can be estimated in terms of the frequency (f, in Hz) and percent flicker (p, in percent) as follows (Bullough et al. in press):

$$d = [(25p + 140)/(f + 25p + 140)] \times 100\%$$

The detection data from the study by Bullough et al. (in press) are shown in the contour plot in Figure 2, as a function of flicker frequency and percent flicker. Also shown in Figure 2 are the frequency and percent flicker values for several common light sources.

This equation is applicable to frequencies from 100 to 10,000 Hz and for percent flicker values from 5% to 100%. The visual task used to assess stroboscopic effects was waving a light-colored rod against a dark background (Bullough et al. in press), and represents close to a worst-case scenario for detection of stroboscopic effects.

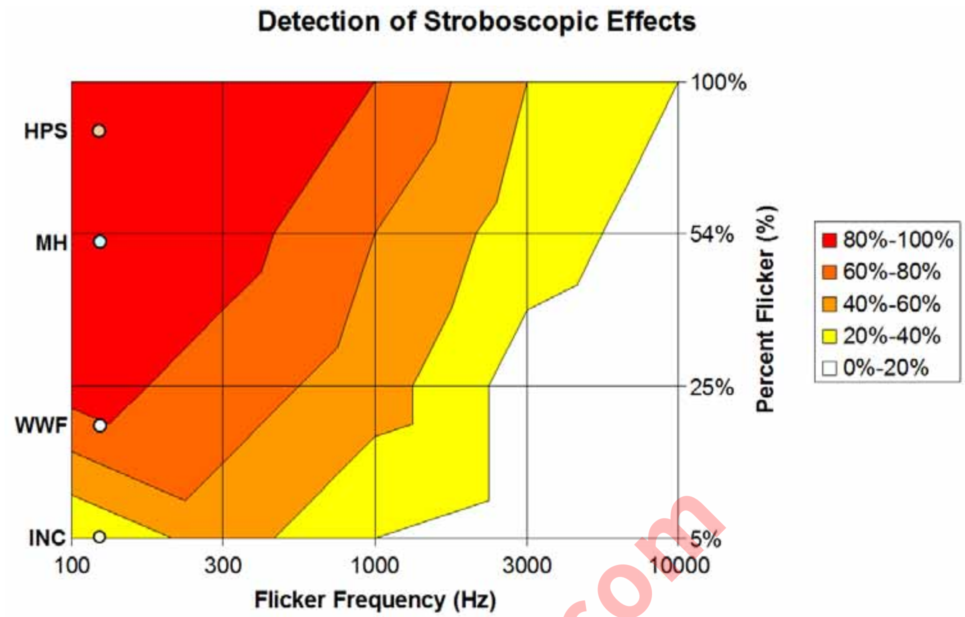


Figure 2. Mean measured detection percentages for stroboscopic effects by light sources varying in flicker frequency and percent flicker (Bullough et al. in press). Also shown are the locations of several common light sources in terms of flicker frequency and percent flicker (HPS: 250 W high pressure sodium lamp; MH: 250 W metal halide lamp; WWF: 40 W warm-white halophosphor fluorescent lamp; INC: 100 W incandescent lamp).

Acceptability of Stroboscopic Effects

To assess acceptability of flicker producing noticeable stroboscopic effects, a five-point scale was used by Bullough et al. (in press):

+2 very acceptable
+1 somewhat acceptable
0 neither acceptable nor unacceptable
–1 somewhat unacceptable
–2 very unacceptable

The acceptability data from the study by Bullough et al. (in press) are shown in the contour plot in Figure 3, as a function of flicker frequency and percent flicker. Also shown in Figure 3 are the frequency and percent flicker values for several common light sources. None of the mean acceptability ratings were below –1.

The data in Figures 2 and 3 suggest that even when stroboscopic effects from flicker were readily detected, they were not always judged as unacceptable. For example, at 1000 Hz, detection of stroboscopic effects (Figure 2) was highly dependent upon the amount of modulation (percent flicker), but ratings of acceptability (Figure 3) were relatively high regardless of the percent flicker value.

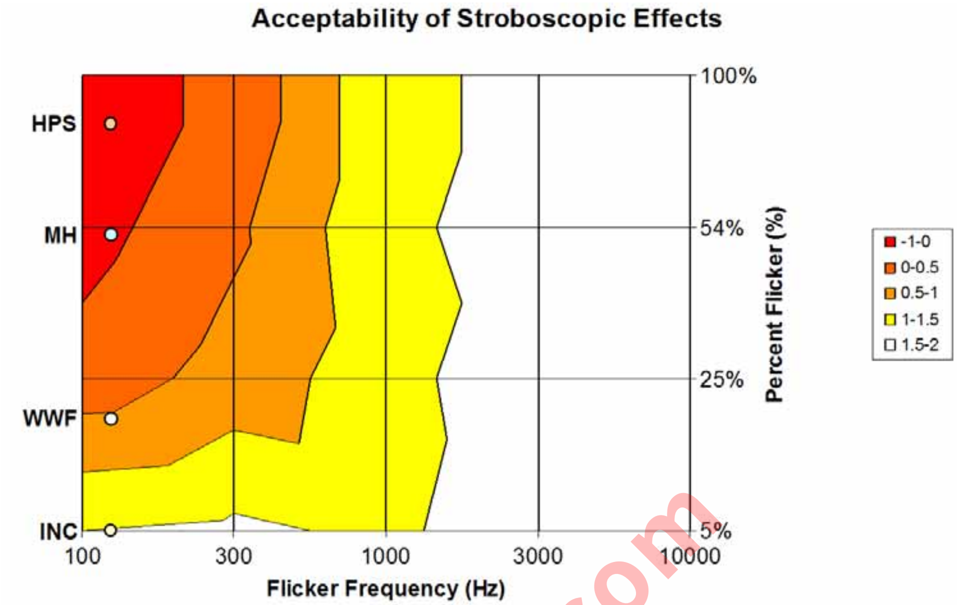


Figure 3. Mean measured acceptability ratings for stroboscopic effects by light sources varying in flicker frequency and percent flicker (Bullough et al. in press). Also shown are the locations of several common light sources in terms of flicker frequency and percent flicker (HPS: 250 W high pressure sodium lamp; MH: 250 W metal halide lamp; WWF: 40 W warm-white halophosphor fluorescent lamp; INC: 100 W incandescent lamp).

For rectangular waveforms operated so that the maximum and minimum light output are produced 50% of the time, the predicted acceptability (*a*, using the scale above) of noticeable stroboscopic effects can be quantified in terms of the frequency (*f*, in Hz) and percent flicker (*p*, in percent) as follows (Bullough et al. in press):

Step 1. Determine the frequency corresponding to the borderline between acceptability and unacceptability, f_b

For a given percent flicker value (*p*, in percent), the frequency at which a rating of zero, corresponding to the borderline between acceptability and unacceptability of stroboscopic effects (f_b, in Hz), is calculated as follows:

$$f_b = 130 \log p - 73$$

Step 2. Estimate the acceptability, a

For a given flicker frequency (*f*, in Hz), and using the borderline frequency (f_b, in Hz) calculated in Step 1, the resulting acceptability (*a*, based on the scale above) can be estimated as follows:

$$a = 2 - 4/(1 + f/f_b)$$

This equation is applicable to frequencies from 100 to 10,000 Hz and for percent flicker values from 5% to 100%. The visual task used to assess stroboscopic effects was waving a light-colored rod against a dark background (Bullough et al.

in press), and represents close to a worst-case scenario for perception of stroboscopic effects.

Example Calculations

Suppose a light source produces a rectangular waveform with the maximum and minimum light output each produced 50% of the time, with a frequency (*f*) of 350 Hz and percent flicker (*p*) value of 50%. To estimate the percent likelihood of detecting stroboscopic effects (*d*) under conditions similar to those used by Bullough et al. (in press), the following calculation is performed:

$$(25 \times 50 + 140)/(350 + 25 \times 50 + 140) \times 100\% = \mathbf{80\%}$$

Thus, under conditions similar to waving a light-colored rod against a dark background, the light source would be expected to produce noticeable stroboscopic effects 80% of the time.

For 50% flicker, the frequency at the borderline between acceptability and unacceptability (f_b) is calculated as follows:

$$130 \times \log 50 - 73 = 148 \text{ Hz}$$

Using a value for f_b of 148 Hz, the estimated acceptability rating for this condition is:

$$2 - 4/(1 + 350/148) = \mathbf{+0.81}$$

Thus, under conditions similar to waving a light-colored rod against a dark background, the light source would be expected to elicit an average acceptability rating of +0.81, corresponding approximately to somewhat acceptable.

Application of Calculation Methods

Because the study that assessed stroboscopic effects (Bullough et al. in press) used a light-colored, rapidly moving object viewed against a dark background, it comprises a near-worst-case condition for perception of stroboscopic effects. Slower movements, objects with lower contrast, and the presence of non-flickering light sources such as daylight would all be expected to reduce the likelihood of detecting, and to increase the acceptability of, stroboscopic effects from a flickering light source.

For this reason, a relative criterion for reducing the perception of stroboscopic effects is proposed. Further, a specification criterion based on the detection of stroboscopic effects rather than on acceptability is proposed, because this is likely to result in a more conservative specification. Reducing the detectability of stroboscopic effects is also likely to increase their acceptability, but not vice versa, based on the data in Figures 2 and 3.

Few people consider incandescent lamps to be problematic light sources in terms of flicker or stroboscopic effects, although these sources produce flicker that can result in noticeable stroboscopic effects. A 60 W incandescent lamp, when operated on a 60 Hz AC power supply, produces 8% flicker (Rea 2000). Using data from Rea (2000) and interpolating for a 50 Hz AC power supply, it is estimated that the same lamp would produce 10% flicker. If one desired to limit the detection of stroboscopic effects from an arbitrary light source to be no greater than under a 60 W incandescent lamp operated on 50 Hz AC power, the equation provided in the section above entitled “Detection of Stroboscopic Effects” could be rearranged to solve for the maximum percent flicker value (p_{max}) for a given frequency (f) that would result in stroboscopic effects no greater than those from a 60 W incandescent lamp, as follows:

$$p_{max} = 0.16f - 5.6$$

For example, if a particular driving circuit results in an LED source producing a flicker frequency of 120 Hz, the equation above would predict that the percent flicker value could be up to 14% and the source would not produce stroboscopic effects more perceptible than those from a 60 W incandescent lamp operated on 50 Hz AC power. If the flicker frequency were 250 Hz, the percent flicker value could be up to 34%.

For flicker frequencies higher than 660 Hz, the equation above will yield percent flicker values greater than 100%. This implies that for any frequency higher than this value, any amount of flicker will be less noticeable than that from the incandescent reference condition.

Caveats

As described above, the data underlying the equation in the previous section correspond to the perception of stroboscopic effects from a light source producing a rectangular waveform with the maximum and minimum light output each produced 50% of the time, and for a visual stimulus consisting of a light-colored rod being waved against a dark background, for frequencies between 100 and 10,000 Hz, and for percent flicker values between 5% and 100%. They are also only applicable when the flickering source is the only light source in a space. The presence of daylight from windows or other light sources with different flicker characteristics will reduce the perception of stroboscopic effects.

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Acknowledgments

ASSIST and the Lighting Research Center would like to thank the following for their review and participation in the development of this publication: J.P. Freyssinier, H. Ohlhous, M. Overington, and N. Skinner.

About ASSIST

ASSIST was established in 2002 by the Lighting Research Center at Rensselaer Polytechnic Institute as a collaboration among researchers, manufacturers, and government organizations. ASSIST's mission is to enable the broad adoption of solid-state lighting by providing factual information based on applied research and by visualizing future applications.