Detecting and evaluating flicker from lighting systems during field assessments of lighting installations

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Abstract. This paper provides guidance to practitioners in visual ergonomics and lighting design, as well as lighting specifiers and installers, on how to detect flicker during field surveys of lighting systems and avoid flicker in lighting system upgrades or retrofits. Flicker has been identified as a problem in several lighting installations in different building types. A common perception is that LED lighting systems are flicker-free. Measurements indicate that LED sources can produce as much flicker as fluorescent lamps with magnetic ballasts. While flicker might be invisible to the human eye, it can easily be detected with very simple instruments available to most; namely mobile phones.

Keywords. Light Sources, Field Assessments, Flicker, Detection

1. Introduction

In order to reduce energy use and environmental impact in buildings, lighting systems using light-emitting diodes (LEDs), also known as solid-state lighting (SSL) systems, are becoming increasingly popular. LED lighting indeed has a high energy-saving potential due to the efficacy of the LED sources. Efficacies for current high-quality "white" LEDs are around 100 to 120 lm/W. LED lighting systems also have an extended lifetime compared to other light sources, thus typically require less maintenance. LED lighting systems are capable of providing essentially flicker-free illumination. Nevertheless, many LED lamps or luminaires currently on the market exhibit flicker – even when not fitted with a dimming system. Dimming LEDs can significantly increase flicker, especially when using pulse-width modulation (PWM). Dimming is not addressed in this paper.

Flicker is a problem associated with many light sources. All light sources operated on alternating current (AC) will flicker. Flicker is defined in the IESNA Lighting Handbook as "the rapid variation in light source intensity" (Rea, 2000, p. 10-5).

Flicker of electric light sources can have its origin in the method used for the conversion of alternating current into light, as well as in noise or fluctuating loads on AC power distribution lines. Electrical flicker due to fluctuations in the power lines needs to be separated from photometric flicker. Photometric flicker is a characteristic of the light source itself, including its control gear, and not of the electrical power supply. Examples include the thickness of the filament for incandescent and halogen lamps, phosphor persistence (the length of time phosphor continues to glow after being energised) for fluorescent and coated metal halide lamps, as well as circuit components and circuit designs for electronically ballasted or driven light sources, including light emitting diodes. During operation conventional non-LED light sources typically do not exhibit a zero light output, even during the off-cycle. Phosphor in discharge lamps or the cooling filament continues to glow until the source is turned on again. Flicker is therefore less visible.

Flicker is visible at low frequencies of light source intensity variations. As the frequency increases, i.e. at more cycles per second (Hz), it reaches a "critical fusion frequency" (CFF) at which flicker will no longer be perceived, and an observer will say that the intensity of the light is constant. This occurs, on average at about 60 Hz, but more sensitive people might perceive flicker up to around 100 Hz.

Flicker frequencies of 100 or 120 Hz, which coincide with 50 Hz electricity supply in Europe or 60 Hz electricity supply in North America, respectively, have been known to contribute to headaches and migraine in office workers (Wilkins et al., 1989). While they are typically not visible to an observer, they can thus have an impact on human well-being and health. High risk groups, e.g. observers with photosensitive epilepsy (1 person in 4000), may experience that flicker at frequencies between 3 and 65 Hz might induce seizures, with the highest likelihood of seizures occurring with frequencies between 15 and 20Hz. The onset of photosensitive epilepsy typically coincides with the beginning of puberty, and in the age group from 7 to 20 years, the condition is five times more common than in the general population (IEEE PAR1789, 2010).

CCF is influenced by various factors, such as differences between individuals in physiology, but also differences within individuals with respect to time of day, tiredness, or health conditions at the time. Above the CFF, but up to about 200 Hz, invisible but detectable flicker can occur. It is believed that this detection is also transmitted through the retina (Berman et al., 1990). Recent research suggests that under certain conditions, flicker at frequencies in excess of 1 kHz can be perceived (Roberts & Wilkins, 2012).

2. LED Basics

LEDs emit light via a process known as electro-luminescence. In simplified terms, photons (light particles) are released when electrons pass through junctions between layers of +/- charged semiconductor materials. Light from an individual LED is typically rather monochromatic. Its wavelength-characteristic depends on the semiconductor compounds used and the complexity of the LED layer construction. White light or colors in between the characteristic spectra of individual LEDs can be achieved by combining light from at least three LEDs with primary colors. LEDs with other dominant colors (wavelengths) are also available. White mixed from the three primaries, however, does not really appear to be white. Therefore, a "white" LED, consisting of a blue LED coupled with a yellow phosphor layer, has been developed. It thus combines electro- with photo-luminescence. Different phosphor mixtures can, just as for fluorescent and other discharge lamps, achieve different correlated color temperatures (CCT) and color rendering indices (CRI or R_a).

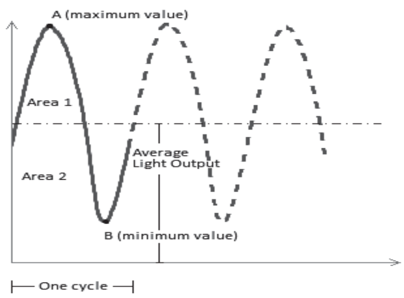
An LED lamp or luminaire is typically made up of several individual LEDs arranged in an array. Every LED has a rated current, which is the amount of electricity that needs to flow to get the maximum light output. The current through the LED therefore determines the LED's brightness. It must be well controlled to ensure that individual adjacent LEDs produce the same brightness, and thus a uniform light level across the array, and to avoid flicker. A string or array of LEDs should normally be driven by a constant current supply. To achieve this, it is necessary to use suitable electronics components in the design of the LED driver which are compatible with the individual LEDs or the LED array used.

3. Flicker Metrics

Flicker has special significance for objects moving within the visual field. Objects may seem to move discretely rather than continuously under flickering illumination. This is known as the stroboscopic effect. It can be dangerous when operating rapidly moving machinery, or just annoying when watching fast sports events, such as table tennis. The magnitude of this effect depends on the frequency and amplitude of the flicker, the rate of object motion, and the viewing conditions. To classify flicker, various metrics have been developed. The most common ones are percent flicker and flicker index.

Percent Flicker (also known as Michelson Contrast or Depth of Modulation) is a relative measure of the cyclic variation in output of a light source (percent modulation). It is given by the following expression, where A is the maximum and B is the minimum light output during a single cycle: Percent Flicker = (A – B) / (A + B) * 100.

The **Flicker Index** has been established as a relative measure of the cyclic variation in output of various sources at a given power frequency. It takes into account the waveform of the light output as well as its amplitude (see Figure 1, left). It is calculated by dividing the area above the line of average light output (Area 1) by the total area under the light output curve for a single curve (Areas 1 and 2). The flicker index assumes values from 0 to 1, with 0 for steady light output. Higher values indicate an increased possibility of lamp flicker, as well as a noticeable stroboscopic effect.



	Percent Flicker	Flicker Index
Average	Yes	Yes
Peak-to-Peak Amplitude	Yes	Yes
Shape / Duty Cycle	No	Yes
Frequency	No	No
Calculation Complexity	Simple	Moderate

Figure 1: Determination of Flicker Index (left, after Rea, 2000, p. 2-32) and comparison of flicker metrics (right, after Poplawski & Miller, 2013, p.191)

Neither percent flicker nor flicker index are ideal flicker metrics. Figure 1 (right) shows the main characteristics of flicker they can address. As we can see, neither method provides information about the frequency at which flicker is detected. Because of this, several other forms of expressing flicker levels have been proposed (e.g. ASSIST, 2012; Poplawski & Miller, 2013), but are not yet widely known.

4. Mobile Phone Video Recordings and Still Images Visualizing Flicker

During field assessments of lighting systems by Aarhus University lighting researchers as part of an International Energy Agency research project (IEA-SHC Task 50), it was observed that video recordings and still images taken of various light sources with a mobile phone (screen refresh rate of 30 frames per second) clearly exposed photometric flicker of light sources. The more modulation occurs in a video, the more flicker is present from the light source. A search of the available literature revealed that other researchers had made the same discovery (e.g. Kitsinelis et al., 2013). Figure 2 shows a selection of such mobile phone still images taken of various light sources at Aarhus University. Where regular stripe patterns occur in a still image, flicker (mostly at twice the power supply rate) is also clearly detectable. Note that the circular and square-shaped (42W) LED sources (2 left pictures) do not exhibit flicker. The rectangular LED panel (26W), however, does. Here, the combination of LED array and driver is apparently not suitable. When the same LED panel was directly connected to a constant and direct current (DC) power supply (rather than AC power and driver), flicker was not detectable with the mobile phone.

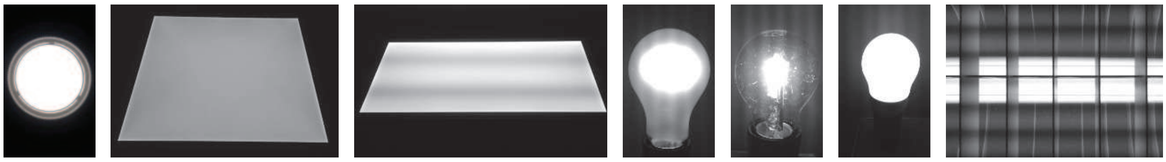


Figure 2: From left to right – still images taken by mobile phone of 12W circular recessed LED luminaire, two LED panels with 42W (square) and with 26W (rectangle), respectively, 150W frosted incandescent lamp, 42W clear incandescent halogen, 14W compact fluorescent, and 36W-T26mm fluorescent lamps with conventional ballast.

5. Flicker Measurements

To scientifically assess flicker occurring when operating these different conventional and LED light sources, measurements were conducted to determine percent flicker and flicker index for a variety of incandescent, halogen, compact fluorescent, linear fluorescent, high-intensity discharge and LED light sources. The set-up for the measurements (Figure 3) consisted of a Si-PIN photodiode detector (United Detector Technology, Model No. UDT MWO4254) connected to an oscilloscope (Agilent Technologies, Model No. HP54621A). Power was supplied at 230V and 50Hz.

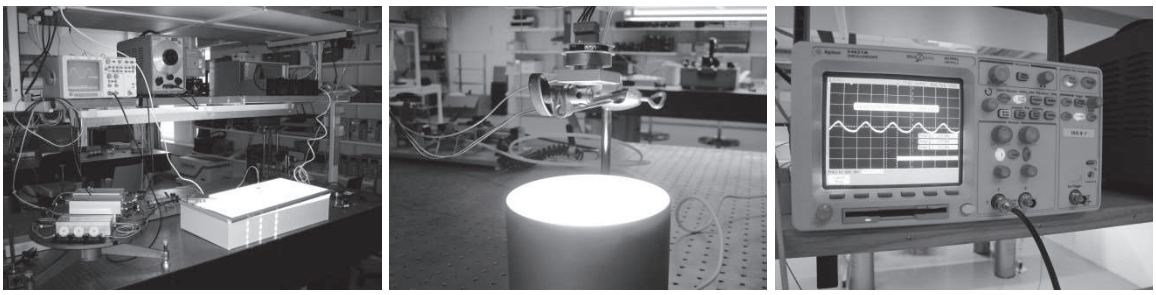
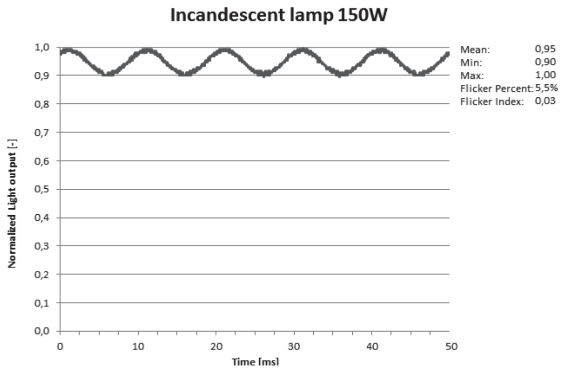
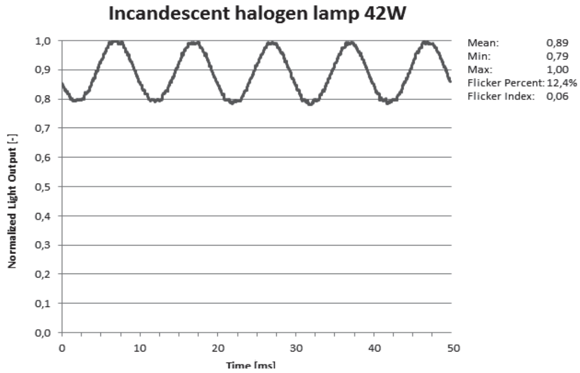


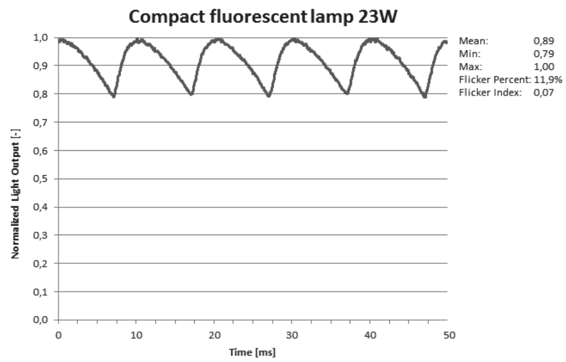
Figure 3: Experimental set-up in Aarhus University's optics laboratory.

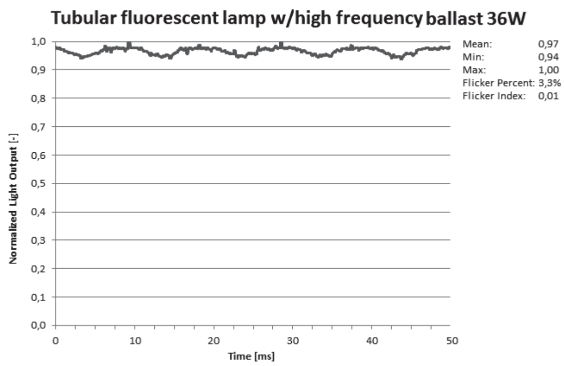
6. Results

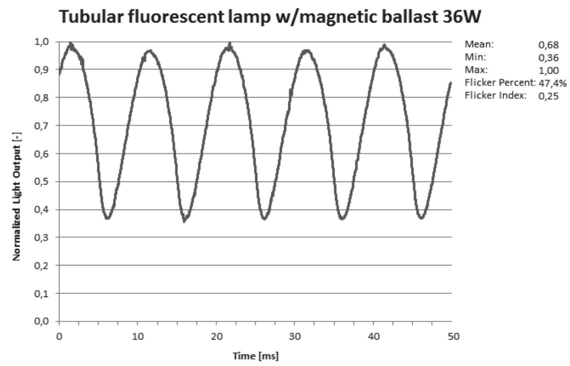
Figure 4 illustrates some of the measurement results from the flicker assessment. Flicker measurements made in Aarhus were generally consistent with those reported by Kitsinelis et al. (2013) and Poplawski & Miller (2013). It could be noted that, although LED sources were operated with direct current via a driver converting AC power into DC power, some of them showed essentially no modulation at all, while others showed a modulation with percent flicker exceeding 40%, i.e. in the same order of magnitude as conventionally ballasted fluorescent luminaires. This clearly indicates that a suitable combination of light source and driver is essential for proper operation of solid-state lighting. The suitability of the driver is determined by the quality and compatibility of the electronic components in both LED source and driver.

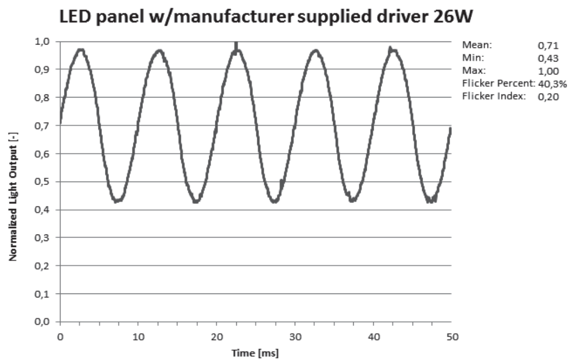

Incandescent lamp 150W
Mean: 0,95
Min: 0,90
Max: 1,00
Flicker Percent: 5,5%
Flicker Index: 0,03
Normalized Light output [-]
Time [ms]

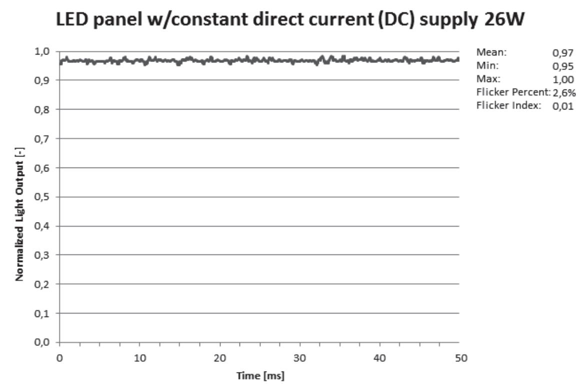

Incandescent halogen lamp 42W
Mean: 0,89
Min: 0,79
Max: 1,00
Flicker Percent: 12,4%
Flicker Index: 0,06
Normalized Light Output [-]


Compact fluorescent lamp 23W
Mean: 0,89
Min: 0,79
Max: 1,00
Flicker Percent: 11,9%
Flicker Index: 0,07
Normalized Light Output [-]
Time [ms]


Tubular fluorescent lamp w/high frequency ballast 36W
Mean: 0,97
Min: 0,94
Max: 1,00
Flicker Percent: 3,3%
Flicker Index: 0,01
Normalized Light Output [-]
Time [ms]


Tubular fluorescent lamp w/magnetic ballast 36W
Mean: 0,68
Min: 0,36
Max: 1,00
Flicker Percent: 47,4%
Flicker Index: 0,25
Normalized Light Output [-]
Time [ms]


LED panel w/manufacturer supplied driver 26W
Mean: 0,71
Min: 0,43
Max: 1,00
Flicker Percent: 40,3%
Flicker Index: 0,20
Normalized Light Output [-]
Time [ms]


LED panel w/constant direct current (DC) supply 26W
Mean: 0,97
Min: 0,95
Max: 1,00
Flicker Percent: 2,6%
Flicker Index: 0,01
Normalized Light Output [-]
Time [ms]

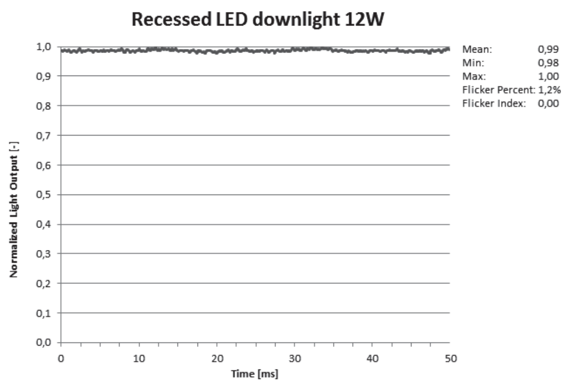

Recessed LED downlight 12W
Mean: 0,99
Min: 0,98
Max: 1,00
Flicker Percent: 1,2%
Flicker Index: 0,00
Normalized Light Output [-]
Time [ms]

Figure 4: Comparison of modulation shape and amplitude, calculated percent flicker and flicker index for various tested light sources on a normalized scale, where "Mean" = average light output, "Min." = minimum light output, and "Max." = maximum light output.

7. Conclusions

Despite the inherent ability of LED light sources to produce essentially flicker-free lighting, many commercially available LED products do not live up to this potential. It is essential that manufacturers of LED lighting systems address this problem in order for the general public to adopt LED technology. While none of the tested sources exhibited visible flicker, flicker could be nevertheless detected with the use of a simple mobile phone camera for many of the sources, including incandescent lamps which few people would perceive to create flicker problems. While the range of lamps tested was limited and did not allow for the establishment of patterns for flicker behavior of specific types of light sources, flicker measurements confirmed that LED sources exist, which – through appropriate combinations of LED array and driver electronics – achieve essentially flicker-free operation of the light source. It appears that simple mobile phone cameras with a screen refresh rate 30 frames per second can be very useful tools for fast and simple flicker checks by lighting designers and researchers when conducting field lighting surveys, selecting suitable luminaires for an installation, or for the initial classification of light sources for more detailed flicker research. Even general consumers can utilize such tools when trying to avoid undesirable side- or after-effects associated with invisible flicker. It can thus be recommended to lighting designers, specifiers and consumers, to employ the simple tools contained in most mobile phones today.

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