PROPOSING MEASURES OF FLICKER IN THE LOW FREQUENCIES FOR LIGHTING APPLICATIONS

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Abstract: **The IEEE Standards Working Group, IEEE PAR1789 *"Recommending practices for modulating current in High Brightness LEDs for mitigating health risks to viewers"* has been formed to advise the lighting industry and standards groups about the emerging concern of flicker in LED lighting. This paper intends to introduce new measures and definitions of lamp flicker in lighting. The discussion represents on-going work in IEEE PAR1789 that is vital to designing safe LED lamp drivers.**

I. Introduction

Flicker from electric light sources has been a concern for several decades. Whether visible or invisible flicker, for some populations it can be a trigger for headaches, migraines, fatigue, epilepsy, and other neurological responses. Flicker has been shown to degrade reading performance, provide a distraction or annoyance for sensitive individuals (including subtle changes in behavior in vulnerable groups), and interact with moving machinery to endanger industrial workers (see (IEEE PAR1789, 2010; Veitch, 1995) for extensive reference list on health effects of flicker).

Magnetically-ballasted fluorescent, metal halide, and high pressure sodium lamps on a 60 Hz electrical distribution produce a 120 Hz modulation in light output. This has been managed in past decades by alternating sources on a 3-phase electrical system, or by using high-frequency electronic ballasts. Concern about flicker is returning with the introduction of solid-state lighting (SSL). Light-emitting diodes (LEDs) may modulate in light output, and depending on the circuitry, the depth of modulation can create a flicker that is more visible or detectable than designers and engineers have dealt with in the past. Even if an LED produces steady-state output, the interaction with common dimmers may produce flicker.

Flicker metrics have been developed in the past, but none of these included frequency as a variable. This paper explores current metrics in the interest of developing an effective metric that will help identify problematic products before they have a chance to affect sensitive populations. The characterization of flicker is challenging, and a technique for collecting waveforms, discussed here, will help quantify the range of luminous flux modulation LEDs can produce. These waveform plots can be used, as a tool for characterizing flicker from SSL and dimming systems.

There has been emerging concern about health effects in lighting due to "invisible" flicker (IEEE PAR1789, 2010). Most humans are unable to perceive flicker in light above 60-90Hz, but there still remain measurable biological effects above the critical fusion frequency. ERG (electroretinogram) responses indicate that invisible flicker is transmitted through the retina, even up to 200Hz (Berman,1991). Some researchers have shown that this flicker may lead to headaches and eye strain (IEEE PAR1789, 2010; Wilkins 2010). Older fluorescent lighting with magnetic ballast is known to have flicker at twice the AC Mains line frequency (100Hz/120Hz). This is also the case with some new LED lighting technologies. IEEE Standards PAR1789 group on LED flicker is examining these concerns and providing recommended practices to the community. This paper represents important concepts that are emerging from IEEE Standards PAR1789 that may be necessary to define how to measure flicker.

A difficulty with existing definitions of flicker is that they do not discriminate between low frequency and high frequency flicker. However, for high enough frequency, there are no retinal biological effects due to flicker. Thus, it is important to change the concepts of how to measure flicker in lighting to include frequency dependence. This paper provides the following:

- Explanation as to why existing definitions of flicker are inadequate to give recommendations on safe flicker frequencies.
- Introduction of new flicker definitions more suitable for lighting designers.
- Examples and experiments to substantiate the relationships between the new measures of flicker.

Although this paper does not give recommendations for safe modulating frequencies or depth of flicker modulation, it provides the first, important step to doing so for the LED lighting industry by proposing precise

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flicker measures. This has been lacking in the literature, but it is vital for the power electronic engineer when designing the driver for the LED light engine. For example, such measures and definitions are required when selecting any output capacitance and control schemes for power factor correction circuitry in the LED lamp.

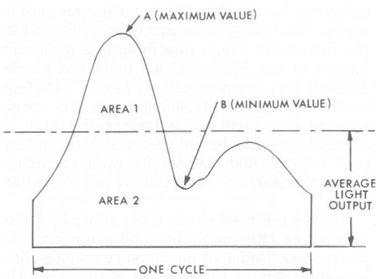

Figure 1. Defining Flicker Index and Percent Flicker (IES Lighting Handbook, Kaufman, 1984)

II. Flicker

A. Definitions

Flicker: a rapid and repeated change over time in the brightness of light.

According to the IES (Illuminating Engineering Society), there are two measures of flicker that have commonly been proposed by lighting designers. The Flicker Index (Eastman and Campbell, 1952; Kaufman, 1984) is often used to measure the relative cyclic variation of the output of different light sources. Referring to Fig. 1 the Flicker Index is defined as the area above the line of average light divided by the total area of the light output curve for a single cycle. Mathematically, this leads to the relation in Fig. 1 of

Flicker Index = (Area 1)/(Area 1 + Area 2) (1)

Percent Flicker = 100 (Max – Min)/(Max +Min) = (A-B)/(A+B). (2)

According to the IES Lighting Handbook (Kaufman, 1984), the Flicker Index is preferred over Percent Flicker. However, Percent Flicker is more commonly found, compared to Flicker Index in research fields such as photobiology and visual science (Wilkins, 1995; Boyce, 2003). This is alternatively called Peak-to-Peak Contrast, Michelson Contrast, or Modulation (Wilkins, 1995).

None of the definitions of flicker in the literature directly provides the necessary information on whether the associated flicker is in the frequency range of health effects or risks. Specifically, above a certain frequency, light may not induce human biological effects, and therefore it is not necessary to limit flicker for all frequencies of modulations. It is common that a signal is composed of several signal frequencies, particularly when switching power supplies are used to drive LED strings. Thus, the above definitions need to be expanded upon before they can be used to assess health effects and risks in LED lighting. See (IEEE Standards PAR1789 public report, 2010) for introduction on how flicker may occur in LED lighting.

B. Perceivable vs. Imperceptible Flicker

Critical flicker fusion and the intrasaccadic perception of flicker

Critical flicker fusion (CFF) refers to the frequency at which flicker is no longer perceived when a flickering source is observed directly, and estimates of flicker fusion frequency usually take no account of eye movement. Here we argue that estimates of flicker fusion are insufficient to guide the design of lighting because of the speed with which the eyes move.

When the eyes move in a jerk (saccade) the angular velocity reaches a peak that ranges from 10 to 700 deg/sec depending on the amplitude of the saccade (Eizenman et al., 1984). Normally, mechanisms of saccadic suppression (thought to be largely central in origin; Breitmeyer and Ganz, 1976) prevent the processing of the image during the saccade. The clear images before and after the saccade act to suppress the intrasaccadic image, partly because it is “smeared”. When the scene is flickering, however, the image that is swept across the retina during a saccade is less “smeared” and it is spatially periodic. This interference with saccadic suppression though normally imperceptible, may be one of the reasons why intermittent light that is too rapid to be seen as flicker can nevertheless affect eye movement control (Kennedy and Murray, 1993).

Sometimes the spatially periodic image during a saccade becomes disruptively visible. For example, when driving at night the flickering LED tail lights of the car in front may appear as a trail of points in anomalous locations. The spatially periodic intrasaccadic stimulus from the tail light is no longer masked because at night there is no competitive clear image before and after the saccade.

Data from Fukuda (1979) suggest that retinal spatial resolution is involved in flicker perception. CFF for small spots was determined first while fixating on a flickering target and then on a moving spot that oscillated sinusoidally across the target. The fixed background luminance and the imposed sinusoidal test flickering source of 100% modulation depth and of about 1 deg in size were both set at 30 cd/m2. Fukuda showed for his young subjects that the subjectively reported CFF under conditions of various eye movements could be about

double that reported under the fixed condition. Note that in tracking a sinusoidally oscillating point, the eyes were performing mainly smooth pursuit eye movements, and any saccades would have been few, small and slow.

Estimation of intrasaccadic flicker

When the eyes are fixating normally, a spatially periodic pattern can be seen most readily when it has a spatial frequency of about 4 cycles/degree, at which spatial frequency patterns with contrasts as low as 0.5% are visible. At maximum contrast, the pattern can be seen at spatial frequencies as high as 30 cycles/degree. Were these considerations to apply during a saccade then bright flicker at frequencies as high as 700 deg/sec x 30 cycles/deg = 7kHz might be visible as a spatial pattern, although visibility of the pattern should be greatest at 700 x 4 = 2.8kHz. However, these estimates ignore two important considerations.

1. During saccadic eye movement there is a loss of contrast sensitivity over and above any loss attributable to masking or to retinal smear. Volkmann et al (1978) measured the contrast sensitivity of three human observers to sinusoidal gratings presented in brief (10 msec) exposures. The gratings were presented to the steadily fixating eye and during 6° horizontal saccades. Contour masking before and after the saccade was reduced by a diffuse unpatterned field of view (Ganzfeld), and use of horizontal gratings minimized retinal smear. Contrast sensitivity was reduced by a factor of more than 4 during the saccades and the reduction increased as the spatial frequency of the gratings increased.

2. Retinal cells integrate their signals over a period of time during which intensity and duration trade off against each other. Bloch's law of temporal summation states that $\Delta I x \Delta T$ = constant where ΔI and ΔT are the light pulse intensity and temporal duration respectively. At low light energy levels with large high-velocity saccades and high frequency flicker there may be insufficient variation in energy during the flight of the eye to stimulate the retina cells. We can estimate the likely contribution of such temporal integration from the data of Fukuda. Examining the data on Bloch's law of temporal summation from Hart (1987) shows that for the background level and increment level of the flickering light level each of 30 cd/m^2 the shorter time of 8msec associated with the 32 deg/sec eye movement velocity of Fukuda's study (32deg/sec x4cyles/degr at max sensitivity = 1/8msec per cycle) is less than the time required for full temporal summation a time of order 25 msec. This indicates that the receiving cones did not have enough time to be fully activated and thus the flicker was less detectable for the 32 deg/sec eye movement velocity when compared to the lower velocity of 16 deg/sec and an associated activation time of 16msec. as shown by the Fukuda data (Fig 5). These two features then combine to show that higher frequency flicker could be perceived during eye movements with a maximum in the test flicker frequency detected for the adaptation conditions employed by Fukuda.

Based on the conservative estimates of 4 cycles/deg for maximum spatial sensitivity and a fast eye movement of 400 deg/sec we would have a maximum flicker perception at 4 cycles/deg x 400 deg/sec = 1600 Hz and an associated time interval of 1/1600 =0.625msec. Based on the Fukuda data of adaptation of 30 cd/m^2 at the peak value of 64Hz and for the flicker increment of 30 cd/m^2 the Bloch constant is 30x 16msec = 480msec,cd/m^2 a value somewhat higher but roughly in the region suggested by the Hart reference above. To be assured of temporal summation the minimum luminance increment for the high frequency limit would then be 480/ 0.625 = 768 cd/m^2 a value easily achieved with an LED. These estimates agree well with the following observations.

Empirical observations

Steady light from an incandescent lamp controlled from a DC stabilised supply was directed via an optic fibre to fill a vertical slot 10mm high and 1mm wide with light of luminance 30 cd/m^2. The slot was viewed through the sectored wheel of a light chopper (Model 197 AMETEK Advanced Measurement Technology, Inc., USA) and observed by 5 observers in an otherwise dark room from a distance of 1m. Horizontal saccades varying in size between 10-30 degrees were made across the slot. The light chopper interrupted the light with a square-wave duty cycle at 1, 2 and 3kHz. At 1kHz the intrasaccadic stimulation was clearly and routinely visible as a train of vertical bars. At 2kHz this perception was occasional, and at 3kHz it did not occur and instead a continuous smear was seen. Evidently the intrasaccadic perception of an intermittent source is visible at 1-2kHz. At higher light levels and with larger saccades the frequency limit may be higher.

Relevance

These observations raise the possibility of biological effects of flicker in the kilohertz range. Their relevance for conventional lighting is currently uncertain, although any effects of intrasaccadic flicker perception could be ameliorated by the use of diffusers, indirect lighting, higher light adaptation conditions, longer duty factors (more light and less dark interval) and phased controls for multiple LED's.

C. Flicker in Solid State Lighting (SSL) and Other Lighting Technologies

Any analysis of photometric flicker requires first the ability to measure, accurately and precisely, the modulation of luminous flux emitted from a light source.

At present, a standard procedure for measuring luminous flux modulation does not exist. This task is unlikely to be viewed as overly challenging for those skilled and experienced in instrumentation, although some nuances must be taken into consideration to ensure accuracy and precision.

Photosensors capable of measuring visible light over a wide dynamic range have long existed in the marketplace. Standard practice for many sensor applications includes the digitization of the (typically) analog sensor output, thereby facilitating the use of a wide range of digital signal processing software. The data sampling and processing requirements for this application are well within the range of (relatively) inexpensive and commonly available hardware and software. A simple system consisting of a light-impermeable box, photosensor, transimpedance amplifier, and digital oscilloscope can be used to measure and digitize photometric flicker. In support of the DOE SSL Program, PNNL constructed (Table 1) and configured (Table 2) such a system, with an emphasis on capturing even very high-frequency luminous flux modulation.

Figure 2 shows flicker measured in a variety of traditional light sources using the PNNL system, including examples of incandescent, halogen, and metal-halide technologies (yellow icons), magnetically ballasted fluorescent technologies (red icons) and electronically ballasted fluorescent technologies (green icons). Figure 3 shows flicker measured in a variety of SSL sources, again using the PNNL system. We observe:

- Some SSL products currently on the market have equal or better flicker performance than traditional lighting technology.
- Some SSL products currently on the market are clearly well outside the flicker frame of reference established by traditional lighting technology, and modulating luminous flux in previously unseen manners.
- Flicker index and percent flicker correlate fairly well at lower levels of percent flicker (< 40). However, shape variation captured by flicker index separates otherwise similar (same percent flicker) products at higher levels of percent flicker.
- SSL products currently on the market exhibit wide variation in flicker performance. Flicker performance is directly related to the LED power electronic driver, since luminous intensity is (approximately) proportional to current through the LEDs (Wilkins, 2010; IEEE PAR1789, 2010).

Combining percent flicker and flicker index in an iconic scatter plot creates a frame of reference for discussing flicker. In Figure 4, an icon for many of the lighting technology samples is plotted such that the x-axis corresponds to the measured percent flicker, and the y-axis corresponds to the measured flicker index. A rectangle has been drawn which encloses all plotted traditional lighting sources, thereby forming a flicker frame of reference for traditional technologies. As expected, incandescent sources crowd one corner of the rectangle and the magnetically ballasted fluorescent sources occupy the opposite corner. The examples of traditional lighting sources occupy an area enclosed by a maximum percent flicker of 40%, and a maximum flicker index of 0.15, hereby referred to as the flicker frame of reference. SSL lighting sources lie both inside and outside this rectangle.

It is apparent from the examples presented here that some SSL light products already on the market are modulating light output in ways different from the electric lighting technologies that the industry is familiar with and has relied on in the past. A visual review of modulated luminous flux waveforms from these SSL product examples shows heretofore unseen peak to peak amplitudes, waveform shapes, duty cycles, and frequencies, as well as a large amount of product to product variation. Further analysis using percent flicker and flicker index confirm that many SSL products on the market are outside of the frame of reference established by traditional technologies.

Table1: PNNL flicker measurement system hardware & software

Light impermeable box	In-house
Photosensor	UDT Model 211
Transimpedance amplifier	UDT Tramp
Digital Oscilloscope	Tektronix DPO2014
Data Acquisition	LabVIEW SignalExpress
Data Pre-Processing	Microsoft Excel
Data Processing	Matlab

Table2: PNNL flicker measurement system configuration

Sample rate (MS/s)	100,000
Sampling period (uS)	1
Sampling window (mS)	125
Record length (samples)	125,000
Number of records	10

III. Fourier Components of Flicker

By decomposing a periodic time signal into its Fourier Series components, it is possible to analyze individual frequency components of the flicker. Visual stress

research suggests (Wilkins, 1995; de Lange, 1961; Campbell and Robson, 1967; De Valois, 1980) that it is the amplitude of the low frequency flicker components that must be considered in its relation to the average illuminance. For example, a large visual target of mean luminance 450 cd/sq m flickering at 60 Hz with a modulation of 30% can be seen as flickering while the same target at the lower light level of 40 cd/sq m is below the threshold even for 100% modulation. Similarly, modeling of the ERG response to flickering light, extending well above the perceivable flicker frequency, e.g. up to 200 Hz, can be modeled in several stages. The first stage of the photoreceptors is a temporal low pass filter with cutoff frequency in the vicinity of 50Hz. After this filter, there is subsequent nonlinear process (Burns, 1992). The results in (Berman, 1991) also indicate that there is no measurable ERG output above 200Hz (ignoring saccade movement).

Therefore, since the beginning stage of the retina response is modeled as low pass filter, the signal after this filter will have reduced high frequency harmonics. When such processes occur, it is standard to consider modeling the input signal by its truncated Fourier Series that contains the harmonic components that are of interest and ignoring the input harmonic content that would be severely attenuated at the output. Specifically, assume that a signal is periodic with period T=1/f where f is the frequency of the signal. Defining $\omega = 2*\pi*f$, the signal may be represented by the Fourier Series:

$$x(t) = Xavg + \sum_{m=1}^{\infty} c_m \cos(m\omega t + \phi_m) \tag{3}$$

where X_{avg} is the average value of *x(t),* c_m are the Fourier amplitude coefficients and corresponding to angular frequency $\omega*m$, and ϕ_m represent the angular phase shift for this frequency

From this Fourier Series decomposition, it is possible to define flicker in terms of low frequency signal components that may be of health risk concern. Because we are concerned with the low frequency components of the signal and their relation to an average value, it is proposed to consider a truncated Fourier Series that keeps only the terms within the frequency range $0 < n*f < f_{threshold}$, where the $f_{threshold}$ may depend on application and *n* is an integer. Specifically, $f_{threshold}$ is defined by the user as the upper frequency limit above which has negligible influence on the output. Then, the signal x(t) may be approximated by the *n*-term truncation Xtrunc(t)

$$Xtrunc(t) = Xavg + c_1\cos(\omega t + \phi_1) + c_2\cos(2\omega t + \phi_2) + \ldots + c_n\cos(n\omega t + \phi_n) \tag{4}$$

As the number of Fourier terms increases the approximation of x(t) by Xtrunc(t) improves.

IV. New Measures for Flicker

Flicker Index and Percent Flicker can now be defined in terms of Xtrunc(t) as can other concepts to measure the amount of potentially harmful flicker in a lamp. Specifically, define the following

Consider the truncated Fourier Series representation of x(t) represented by Xtrunct(t) as in (4) with n terms ($n*f < f_{threshold}$, where f = 1/T is the frequency of signal x(t)).

Low Frequency Flicker Index: The Flicker Index of the signal Xtrunc(t), which is composed of only the low frequency harmonic range of index. That is, let *f(t) = max{Xtrunc(t) - Xavg, 0}*. Then

$$LFFI = \frac{\int_t^{t+T} f(\lambda)d\lambda}{\int_t^{t+T} Xtrunc(\lambda)d\lambda} \tag{5}$$

Low Frequency Percent Flicker(LFPF): The Percent Flicker of the signal Xtrunc(t), which is composed of only the low frequency harmonic range of index. Specifically, if Xtrunc(t) is given in (4), then

$$LFPF = \frac{\max\{Xtrunc(t)\} - \min\{Xtrunc(t)\}}{\max\{Xtrunc(t)\} + \min\{Xtrunc(t)\}} \times 100 \tag{6}$$

It is possible to define flicker in terms of the energy or power of each harmonic component. This leads to concepts similar to Total Harmonic Distortion or Total Unwanted Distortion (Krein, 1998):

Low Frequency Flicker Distortion. The ratio of {the square root of the sum of the squares of the unwanted harmonic coefficients} divided by {the average value of the signal}.

$$LFFD = \frac{\sqrt{\left(c_1^2 + c_2^2 + \ldots c_n^2\right)}}{Xavg} \tag{7}$$

$$LFFD_{RMS} = \frac{\sqrt{\left(c_1^2 + c_2^2 + \ldots c_n^2\right)}}{X_{RMS}} \quad ; \quad X_{RMS} = \left(\frac{1}{T}\int_0^T x^2(\lambda)d\lambda\right)^{1/2} \tag{8}$$

Notice that X_{RMS} is the RMS value of x(t) instead of Xtrunc(t). This is because X_{RMS} is directly accessible by oscilloscopes, and it is extra work to calculate the RMS of Xtrunc(t).

LFFD appears to be the simplest to measure experimentally, especially when there are multiple Fourier coefficients to be considered. This is because there is no phase shift dependence on LFFD. Similarly Fu $LFFD_{RMS}$ has no phase dependence and has the advantage of always being a number less than one. None of these above definitions have been proposed by lighting designers for measures of flicker yet, but they seem natural to power electronic designers when multiple low frequencies are present.

V. Simple Example (n=1)

For the case when there is only one single harmonic of interest, then only the c_1 term is used:

1) *Low Frequency Flicker Index* can be calculated independent of the phase shift ϕ_1, and therefore, without loss of generality this phase shift can be assumed zero. Then with noticing the symmetry of cosine functions, the Low Frequency Flicker Index will satisfy:

$$= \frac{\int_0^{T/4} c_1 \cos(\omega t)dt + \int_{T/2}^{3T/4} c_1 \cos(\omega t)dt}{T * Xavg + \int_0^T c_1 \cos(\omega t)dt}$$

This leads directly to

LFFI=Low Frequency Flicker Index = $\frac{1}{\pi}\left(\frac{c_1}{Xavg}\right)$

2) *Low Frequency Percent Flicker* also simplifies noting that the max and min values of Xtrunc(t) are equal to $Xavg+c_1$ and $Xavg-c_1$, respectively. Therefore,

LFPF =Low Frequency Percent Flicker = $100 * \left(\frac{c_1}{Xavg}\right)$

3) Low Frequency Flicker Distortion yields similar answer to Low Frequency Percent Flicker (divided by 100) also

LFFD= Low Frequency Flicker Distortion = $\left(\frac{c_1}{Xavg}\right)$

Several lighting technologies will inherently have approximately only a single harmonic frequency. For example, as the experimental flicker plots show, incandescents/halogens will have a dc component plus a harmonic at twice line frequency. (Even some CFLs experimentally have "approximately" demonstrated this feature.) In these cases (2) approximately reduces to (5) and (3) approximately reduces to (6). That is LFFI is approximately equal to Flicker Index and LFPF is approximately equal to Percent Flicker. For example, referring to the 60W A19 incandescent flicker plot, Percent Flicker was measured to be 6.6%. On the other hand the LFPF is calculated as 100*c1/Xavg, which in this case is 100*0.06/.94 = 6.5%. The small discrepancy is within roundoff error.

Example 1: Consider a simple periodic PWM waveform for the luminous flux output of an LED lamp as shown in Fig. 5, which is also the (approximately) same experimental flicker shape as the R30/PAR30 SSL lamp flicker in Fig. 3. Suppose we define f_{lamp} = 1/T as the frequency of the flicker. The duty cycle, D, varies between 0 and 1 and represents a fraction of on-time for the PWM signal. The Fourier Series of the PWM waveform is given by

$$x(t) = X_{\max}\left(D + \frac{2}{\pi}\sum_{m=1}^{\infty}\frac{\sin(m\pi D)}{m}\cos\left(m\omega\left(t - \frac{DT}{2}\right)\right)\right);$$

$$\omega = 2\pi f_{lamp}$$

For the purpose of illustration, suppose that we are only interested in the first term of the Fourier series, perhaps because $2*f_{lamp} > f_{threshold}$. Then the truncated Fourier series is given by

$$Xtrunc(t) = X_{\max} * \left(D + \frac{2\sin(\pi D)}{\pi}\cos(\omega(t - 0.5DT))\right)$$

Therefore: *LFFD= Low Frequency Flicker Distortion =c_1/Xavg =* $\frac{2\sin(\pi D)}{\pi D}$

For the R30/PAR30 measured flicker in Fig. 3, D= 0.5. Therefore, the LFFD = 4/π = 1.27, or equivalently, the Low Frequency Percent Flicker is equal to 127%. It should be noted that the PWM example represents luminance intensity of common LED lamps on the market. Some modulate at frequencies as low as twice the line frequency (120Hz in US and 100Hz in Europe), while others modulate at frequencies near 1kHz. By defining measures such as above, it is possible to carefully analyze the influences of the individual frequency harmonics on human health and decipher the differences between the different lamps with different frequencies. That is, health effects may not be noticeable at the higher frequencies, as noted in (Wilkins 2010;IEEE PAR1789, 2010).

VI. Final Remarks

Finally, it may be suggested that for very low frequencies, there is no need to limit harmonic content. In this case, we may define a range of frequencies that are of concern $f_{low} < f < f_{threshold}$. For example, when frequencies are below 1Hz, there is reduced risk of photosensitive epileptic seizures (IEEE PAR1789, 2010). Then it is possible to define a modified measure of distortion that only includes the Fourier terms in the frequency range of interest:

Total Unwanted Flicker Distortion (TUFD)

$$TUFD = \frac{\sqrt{\left(c_k^2 + c_{k+1}^2 + \dots c_n^2\right)}}{Xavg}$$

where the undesirable terms in Xtrunc(t) of (6) are the terms associated with $\{c_k, c_{k+1}, \dots c_n\}$ where *n* is as defined in (6), n > k, and $f*(k-1) < f_{low}$ but $f*k > f_{low}$. Of course, in order to make the proposed definitions more meaningful to lighting standards, it is important to define and justify $f_{threshold}$, the upper frequency limit after which lighting may not impose biological concerns. This document does not suggest such a frequency.

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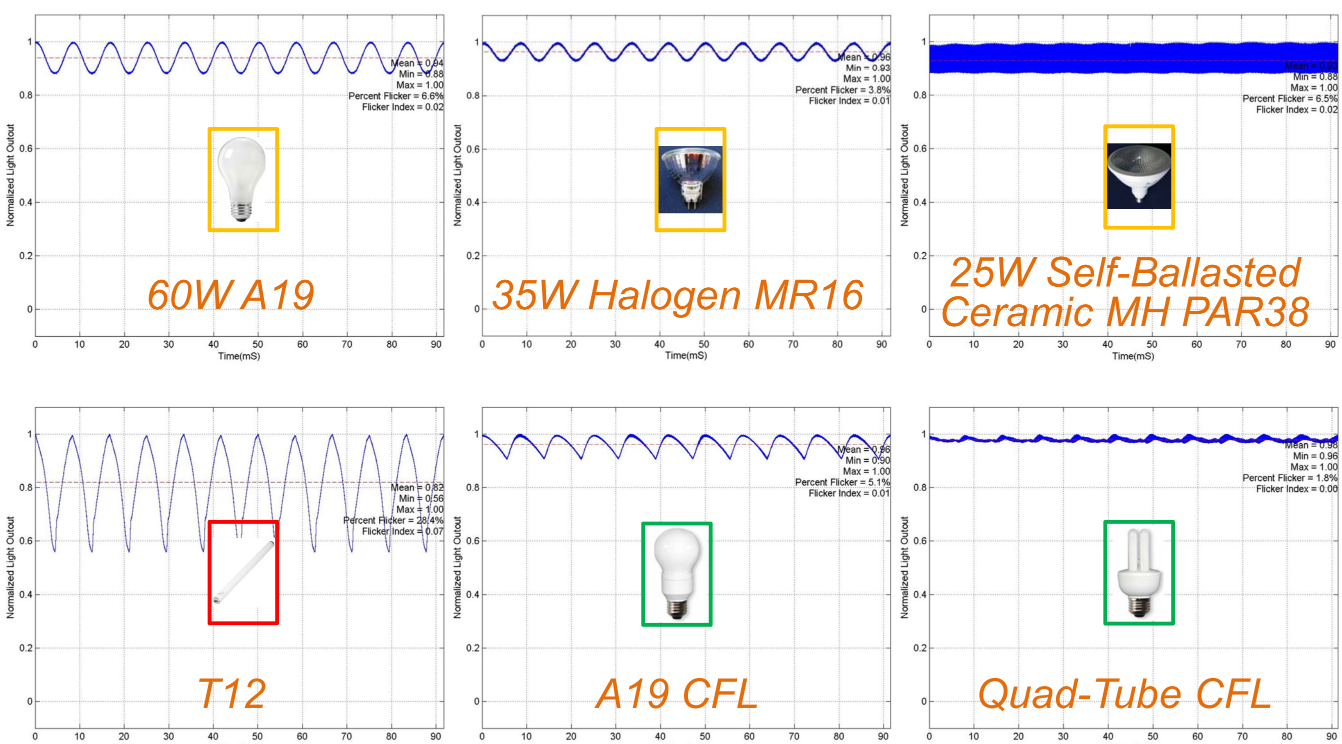

Fig 2. Experimental Data of Flicker in Traditional Lighting Sources

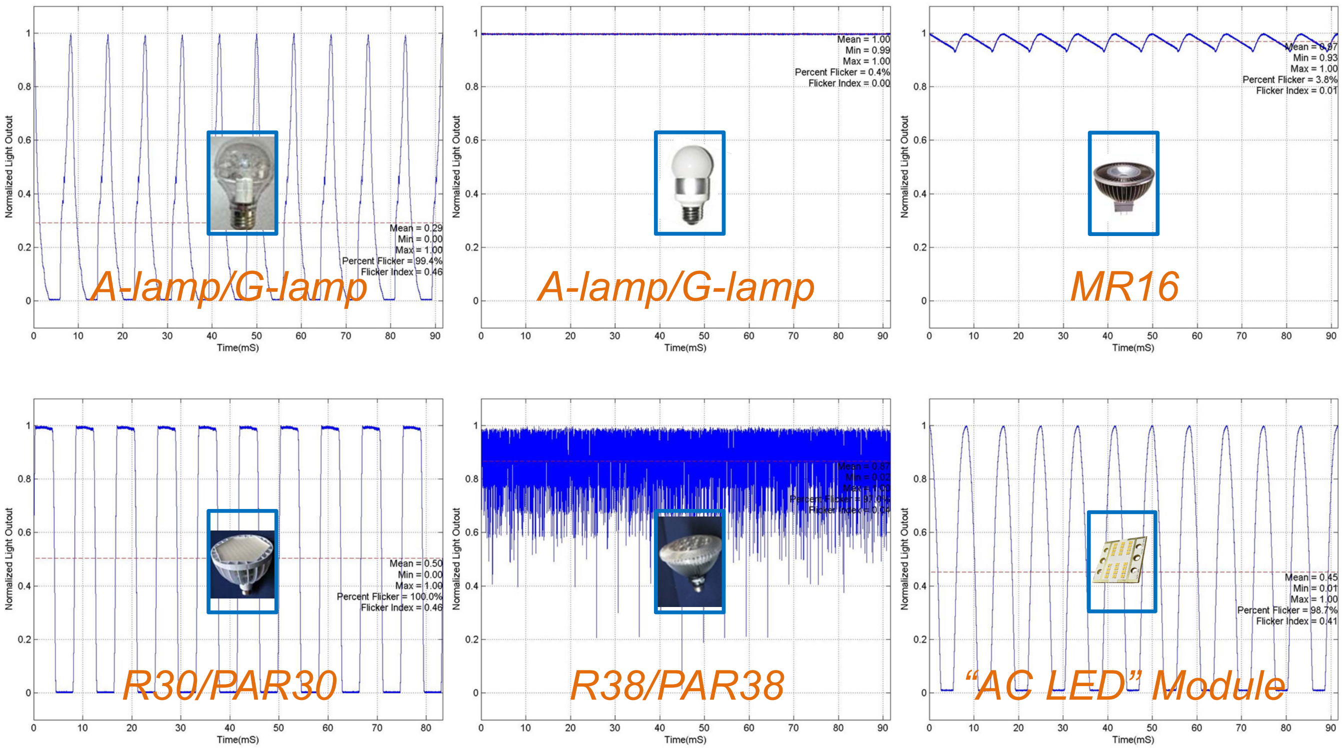

Fig. 3. Experimental Data of Flicker in Solid State Lighting Sources

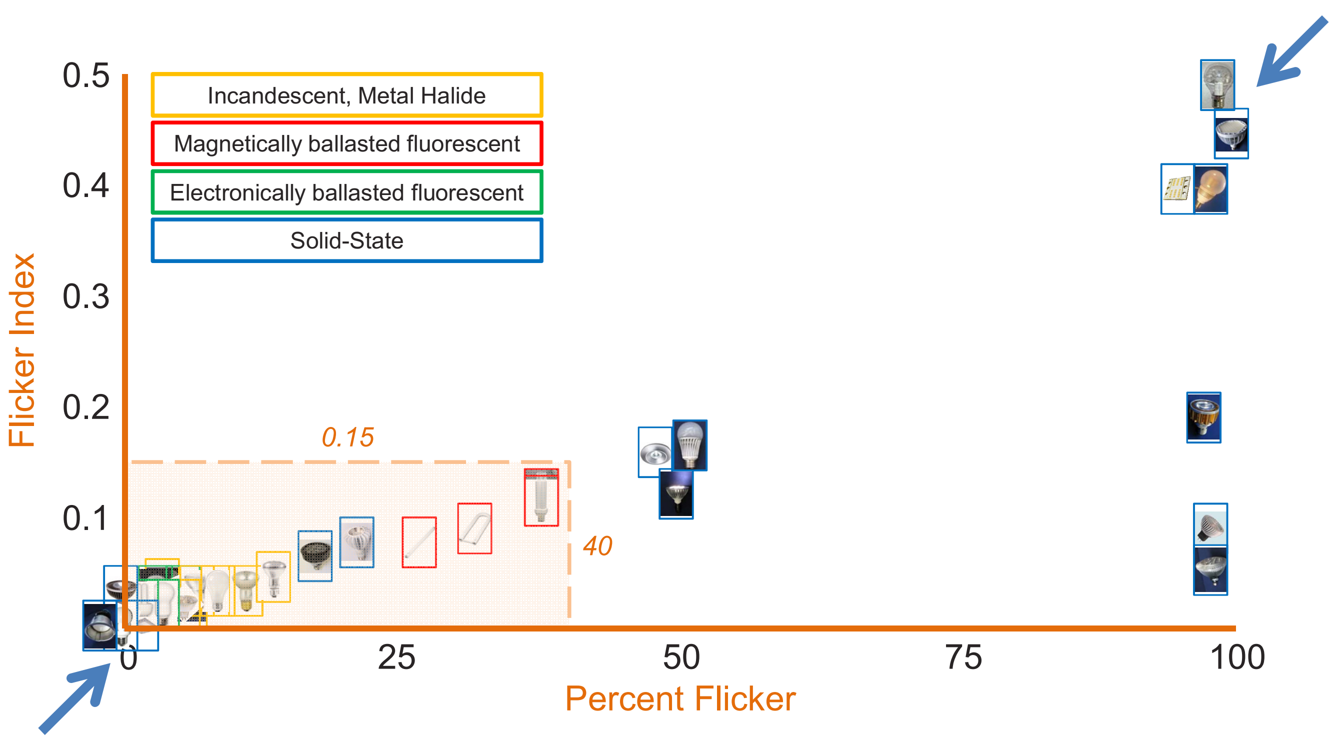

Fig. 4.Examples of Lighting Products on the Flicker Frame of Reference