A NEW FLICKER METRIC AND ITS APPLICATION TO AC LED LIGHT ENGINES

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Human vision is adversely affected by light fluctuations at frequencies up to 200 Hz, even though people can only directly perceive fluctuations at frequencies up to about 70 Hz. The fundamentals of the sensitivity of the human eye to rapidly changing light (transient light artefacts or TLAs) as a function of frequency have been well known to science for a decade or more. Despite this, the lighting industry has so far limited itself to only characterizing light sources over the range of frequencies which the human eye can perceive directly. This range is below 100 Hz. However it is well documented that human visual performance is degraded by the presence of light fluctuations at frequencies in the range from 100 to 200 Hz. At the European LPS2016 conference mathematician Peter Erwin presented a software tool called CFD which can characterize any light source for its flicker acceptability, based on well-known and published characterizations of the human eye/brain interaction as a function of frequencies extended out to 2000 Hz. This tool has met with widespread acceptance in Europe because of its consistency with every day common sense observations, and in particular has been adopted by the German laboratory TÜV Süd as its criteria for characterizing time variant light quality. In this article the history and mathematical basis of the new CFD measure for flicker are introduced and described. Examples of the use of this tool in application to AC LED light engines, fluorescent lamps and incandescent lamps are then given. Using this new tool, it can be seen that some driverless AC LED light engines that use higher frequencies to control the light output have light quality for the human eye which is comparable to an incandescent light bulb.

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There have in recent years been several attempts to create a judgment standard for the acceptability of light containing TLAs. Examples of light containing TLAs are LED lights with PWM dimming, AC LED light engines with 120 Hz modulation and especially LED filament lamps. The basic physiological data for the sensitivity of the human eye to light variations at a given frequency has been well known for many years. For example, see the seminal work of Kelly in 1960, (1) funded by the Technicolor company. Similar studies were reported as part of a doctoral thesis by Farhang Ghasemi Afshar in 2008. (2) In 2016 Pierre Beeckman of Philips provided the sensitivity vs frequency curves shown in Fig.1 which he has presented at various meetings.

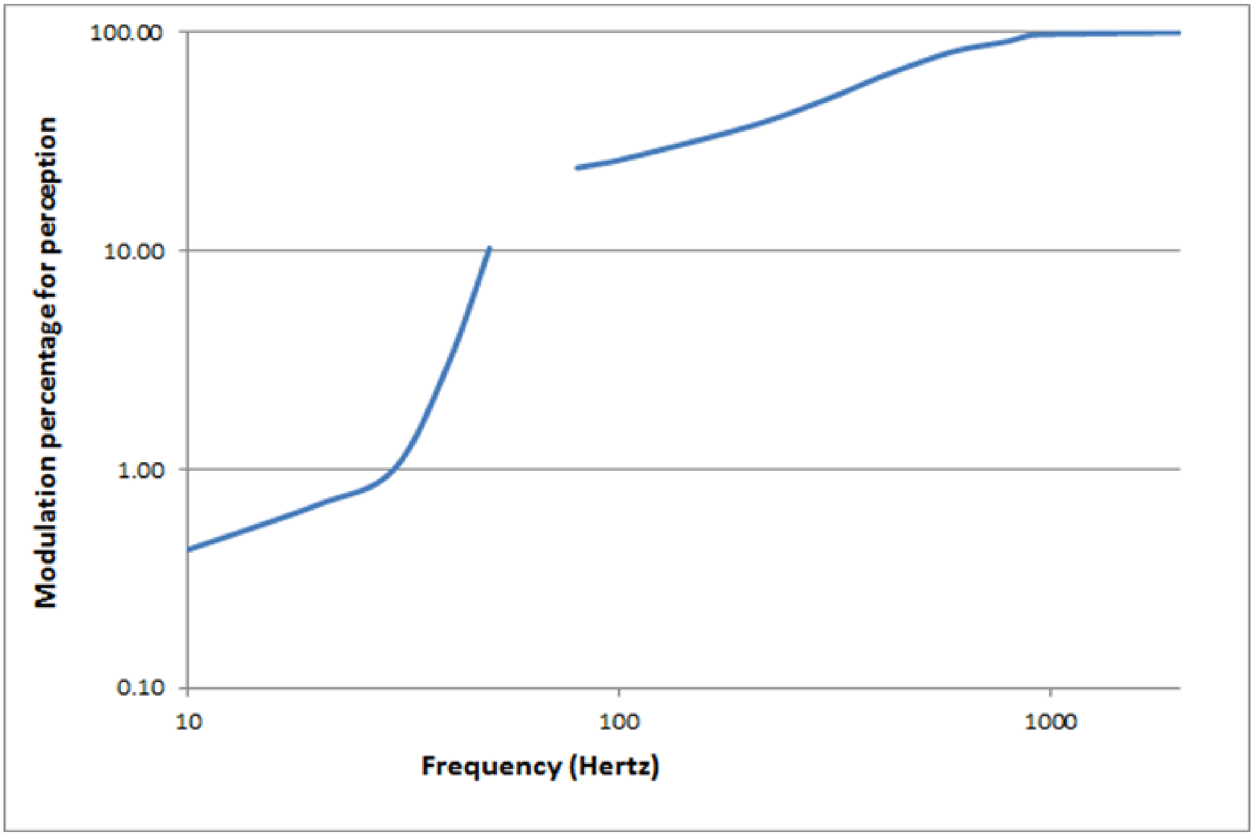

Figure 1. Pierre Beeckman's data for flicker perception

In reviewing this data, the reader needs to be aware that a great deal of statistical variation is involved. For example, in general younger subjects are likely to perceive lower level and higher frequency transient lighting artefacts (TLAs) than older observers can see. Ten different observers will, in detail, produce ten different sensitivities for a given frequency data point. For this reason a commonplace procedure is to derive a signal level which 50% of observers can discern. To add to the complication, the central field of view of the human eye (the macula) is less sensitive to TLAs than the outer parts of the retina, which contribute so called peripheral vision. For this reason there are sometimes shown two response curves, one for central vision and one for peripheral vision. In this article we shall by default mean central vision when perception is referred to. It is also important to realize that the response of the human eye to higher frequencies can be augmented by stroboscopic effects. A rapidly moving object, for example, a pencil, a wand or a spinning disk with radial markings on it, will show a series of images in the presence of flicker at a frequency which is too high for the human eye to observe directly. See for example Fig.2 which shows a moving pencil being illuminated in front of a night-time window by a relatively high flicker content (Flicker index 0.34 at 120 Hz) light source.

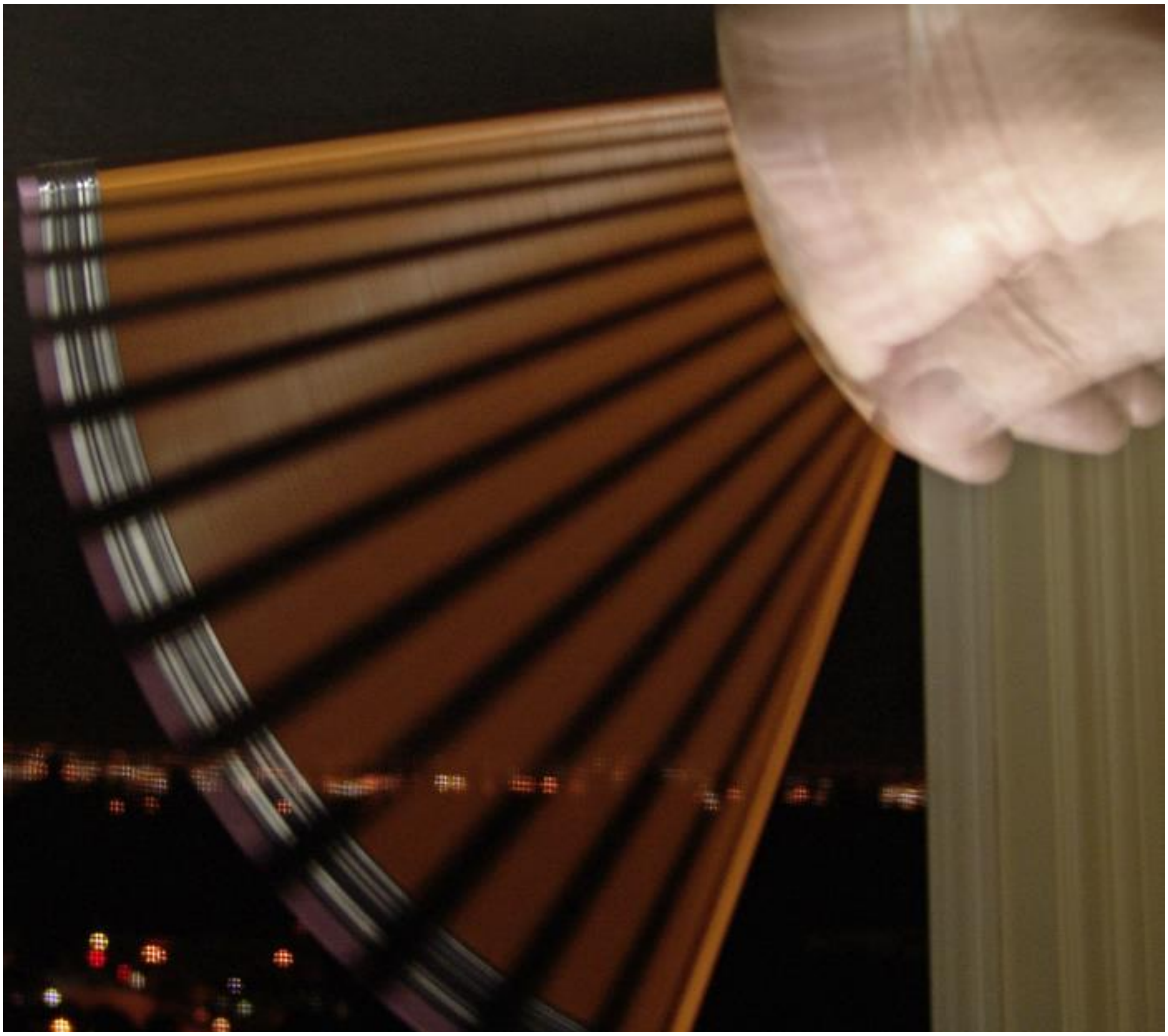

Figure 2. Stroboscopic effect from a moving pencil in front of a light source with a flicker index of 0.34

Graphs of the human eye response commonly have a separate, higher frequency section where the human eye cannot perceive the flicker directly at all, and yet it can be perceived with a mechanical aid such as the moving pencil of Fig.2. A closely related effect takes place when the human eye scans across a light source with high flicker content. Instead of perceiving a single light, the eye may perceive several lights, a so called phantom array. This may sometimes be observed with automotive LED tail lights which may be dimmed at 100 Hz. These effects were described by Roberts and Wilkins. (3) Experiments have shown reproducibly that human beings cannot directly perceive sinusoidal flicker at over 100 Hz. However, there have been experiments which have detected the signal going down the optic nerve to the brain which have shown that the human brain does in fact receive signals at frequencies up to 200 Hz. Berman, 1991,(4). Experiments by Jaen et al. in which subjects were required to perform standard tests under varying light frequencies have shown decreased performance at frequencies between 100 Hz and 200 Hz, even though the subjects could not perceive any flicker. (5)

INTRODUCING FLICKER MEASUREMENTS

There have long existed simple measures of flicker such as the flicker index and percentage flicker, both defined by the IES in RP-16-10. (6). These measures are not frequency sensitive, and are therefore of limited use for characterizing complex waveforms. For example a pulse width modulated (PWM) dimmed LED light operating at 2000 Hz would have 100% flicker even though the light is excellent for all human purposes. An earlier landmark in flicker evaluation was the standard IEEE 1789-2015. This standard attempted to define universally safe levels of flicker. This is a difficult thing to do, and the resulting recommendations (which were only for sinusoidal flicker waveforms) have been a source of controversy in the lighting industry. Fig.3 shows the low risk and high risk flicker levels according to IEEE 1789 with the flicker level of 60Hz Hz and 50Hz incandescent light bulbs shown for comparison.

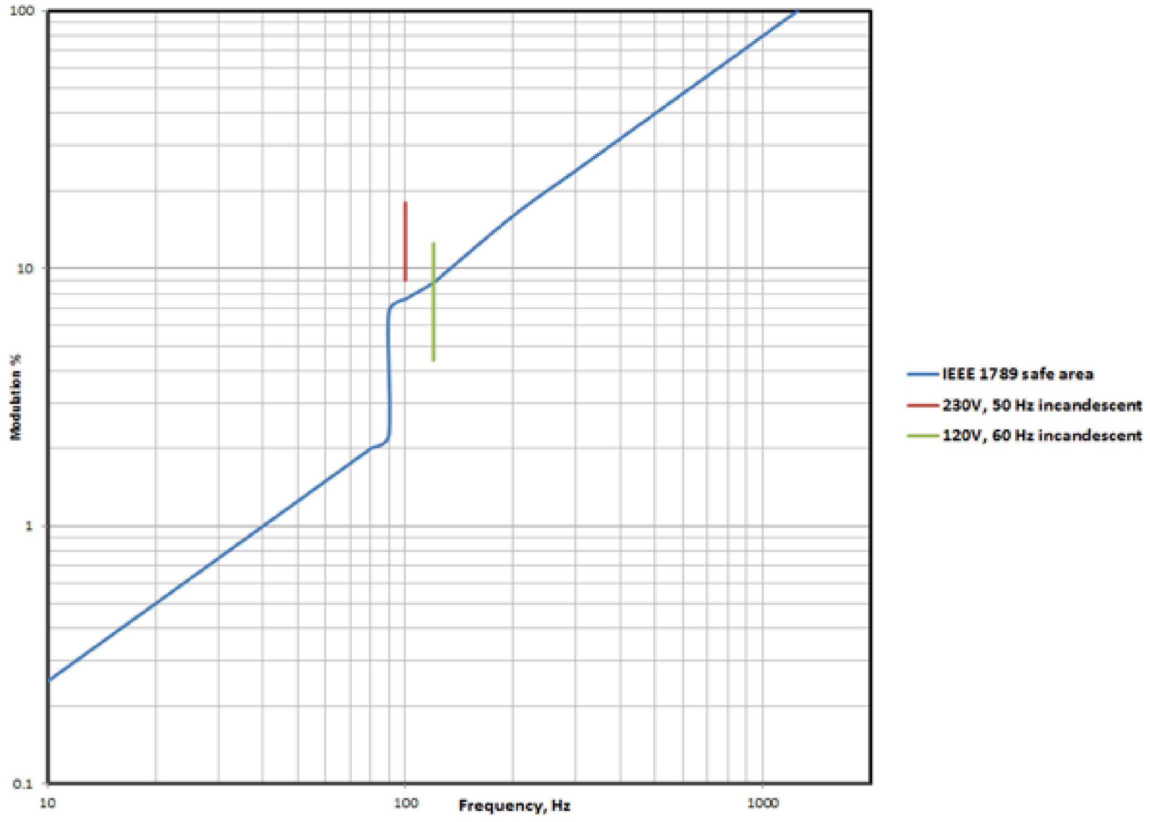

Figure 3. IEEE 1789 safe area curves

Any light source which appears below the line is deemed to be safe according to IEEE 1789. The characteristics of the incandescent bulbs are shown as a line because lamps of different power levels have different flicker levels. Big lamps have the lowest percentage flicker. All of the 50 Hz incandescent light bulbs and some of the 60 Hz light bulbs show up in the dangerous category, which is contrary to a century of experience in the lighting industry. Another criticism of IEEE 1789 is the discontinuity which appears at 90Hz – since this is a reflection of a biological response, then the existence of a discontinuity would seem to be inconsistent. A limitation of the IEEE 1789 approach is that it is basically limited to sinusoidal variations. It is well known that any periodic waveform can be analyzed into its harmonic components (Fourier analysis) which when added together will then comprise the original waveform. So in principle the sensitivity charts of the kind shown in IEEE 1789 could not be used to handle general, non-sinusoidal waveforms. The extension of these kind of charts to generalized waveforms was well described in the publication "Recommended metric for assessing the direct perception of light source flicker" (7) from the Lighting Research Center (LRC - ASSIST). In this publication there is described a good procedure for reliably acquiring a light waveform, resolving it into Fourier components, weighting these components according to human perception and producing a normalized flicker content known as the LRC flicker metric. This has the property that a metric above unity is likely to be perceived, while a metric of less than unity is unlikely to be perceived. The weakness of this metric is that it is well known that there are human flicker sensitivities in the frequency range from 100 Hz to 200 Hz, even though the human eye cannot directly perceive this flicker. Subjects performing standard visual tasks such as searching for something on a page, perform less well when the task is illuminated by such high frequency flicker. (5) Human beings can be confused by stroboscopic effects and by phantom array effects. (3) For this reason Beeckman continued his sensitivity curves out to 2000 Hz, as shown in Fig. 1.

In this article we introduce a new metric, called the "compact flicker degree" or CFD which is similar in nature to the LRC flicker metric. Essentially the work of ASSIST (7) has laid the foundation for the CFD with fast Fourier Transform frequency analysis (FFT) and the computation of the root mean square sum of the weighted individual frequencies. The difference is that CFD takes into account all Fourier frequencies up to 2000 Hz, instead of stopping around 100 Hz. The mathematical construction will allow any frequency range to be used if human response data is available. This metric was first presented at LPS2016 in Bregenz, Austria and has been well received in Europe. Major European laboratories including German laboratory TÜV Süd are preparing to adopt it as a standard. The CFD is presented as a percentage, with higher percentages corresponding to more troublesome flicker. Theoretically the CFD number can be higher than 100% with artificially created waveforms. The sensitivity of the CFD as a function of frequency is shown in Fig.4 by comparison with the IEEE 1789, Beeckman's curves (smoothed) and the measurements of Kelly.

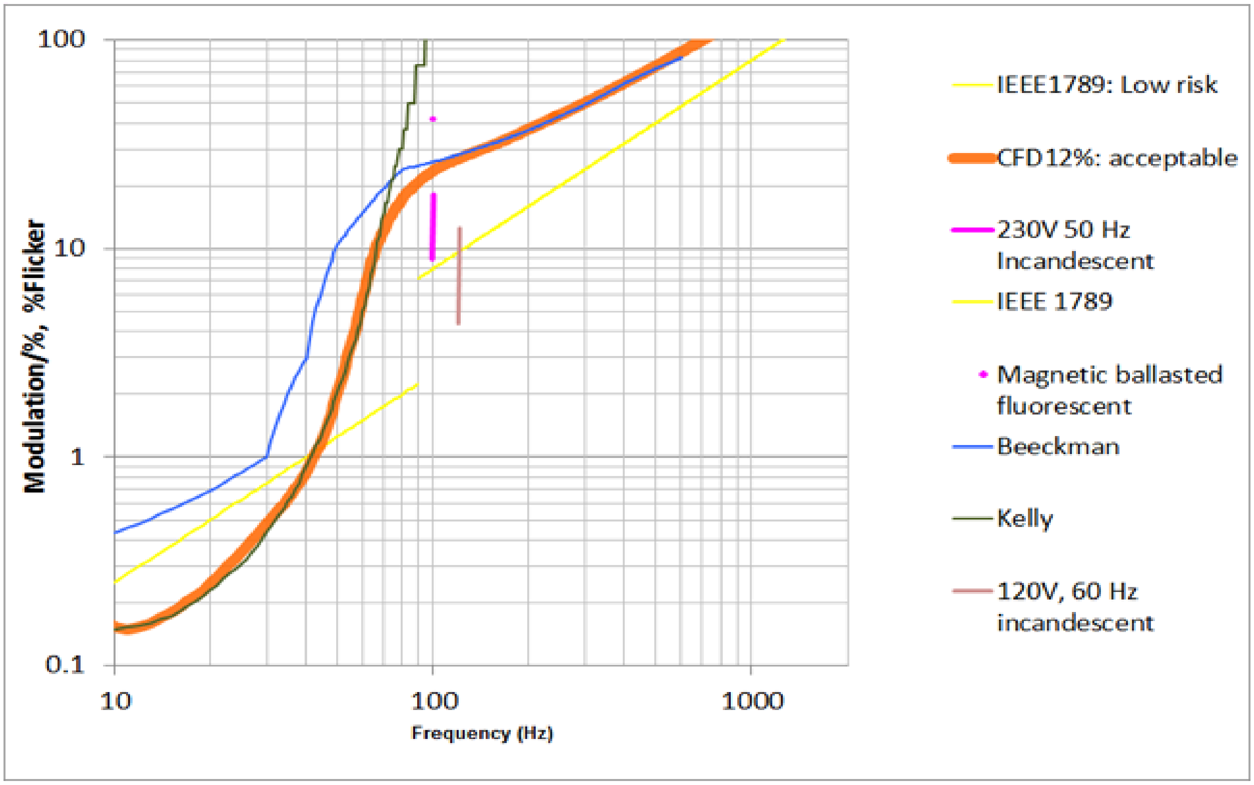

Fig.4 percentage modulation needed for perception as a function of frequency

In interpreting these curves, for a light source like the incandescent bulb and magnetic ballasted tube shown, higher up is worse. For light sources the vertical axis is the % flicker, as defined by the IES. For the human sensitivity curves (Beeckman, Kelly) the vertical axis is the modulation percentage needed for perception, if necessary with a mechanical aid at higher frequencies. For the CFD curve, the vertical axis is the % modulation which will produce a CFD rating of 12% at each individual frequency. By design, the CFD curve follows the data of Kelly at low frequencies and that of Beekman at higher frequencies. The most dramatic observation is that the CFD measure takes account of flicker at frequencies above 100 Hz, consistent with the curves of Beeckman. These frequencies are ignored by the LRC metric. The CFD metric was programmed to follow the data of Kelly up to around 70 Hz, because his work was so well documented. (The data of Beeckman is very similar in nature in this frequency range but systematically higher, perhaps reflecting a difference in the experimental methodology.) At higher frequencies, there is only the data from Beeckman and the CFD response curve is set close to the data from Beeckman on up to 1000Hz. Since Kelly did not incorporate the consequences of stroboscopic effects and phantom array effects, then the Kelly curve rises swiftly to 100% above 70Hz and for this reason the CFD weighting curve follows the data from Beeckman above 100Hz, since Beeckman measured a weighting curve for these frequencies. Beeckman's original data showed a discontinuity between where directly perceived flicker ends and where stroboscopic and phantom array effects begin. Since we are charting a biological response in which every frequency must have some consequence, the CFD weighting curve has been set to interpolate smoothly from the Kelly curve to the higher frequency branch of Beekman's data. Fig.5 shows an assortment of commonplace lighting waveforms with their associated CFD measurements.

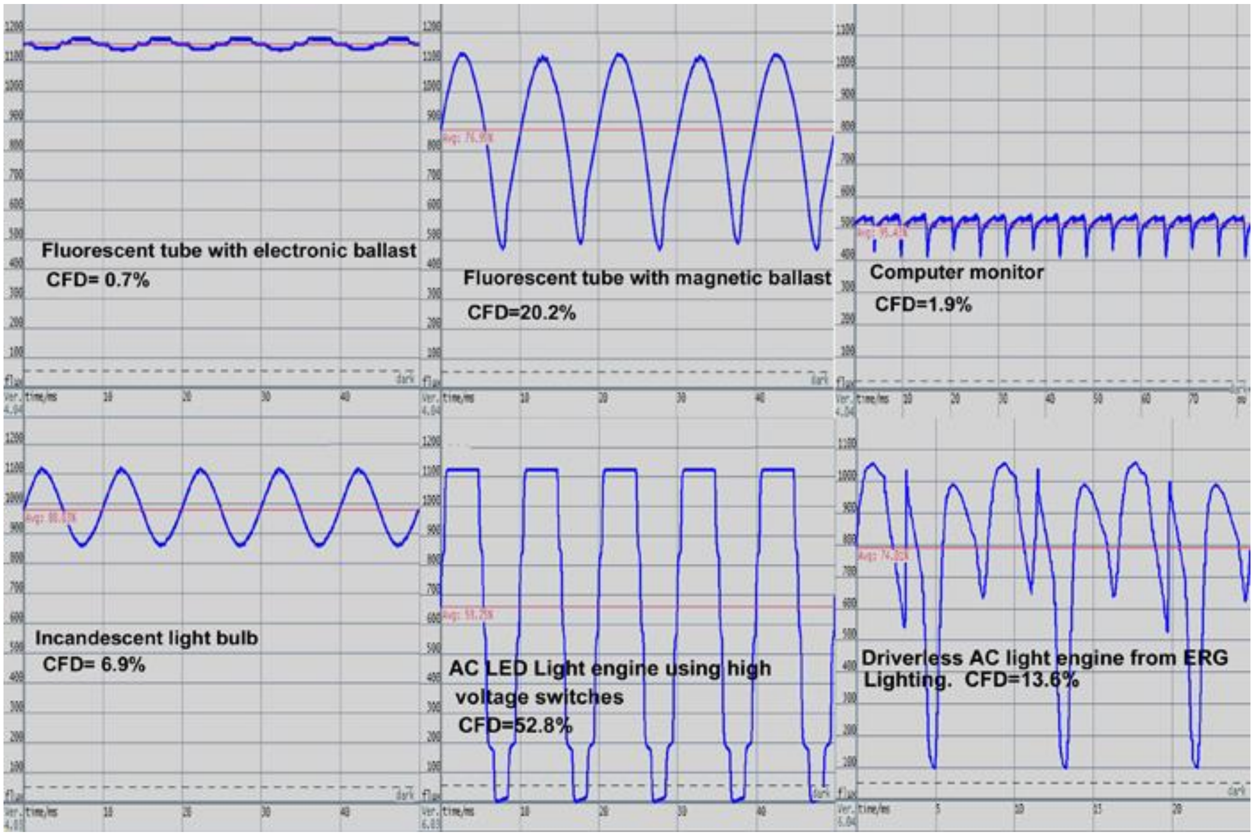

Figure 5. Samples of CFD measurements on various light sources

The incandescent bulb shown has a CFD rating of 6.7% at 100 Hz, for example, however incandescent bulb ratings vary by a factor of two from the largest to the smallest bulbs, with larger (say 300W, 120V) bulbs having the least flicker and smaller (say 50W, 230V) having the most flicker.

INTERPRETING CFD MEASUREMENTS.

The results of CFD measurements are categorized as follows: Less than 1% is classified as “flicker free”. CFD values from 1% to 12.5% are classified as ”imperceptible”. In Figure 4 it is the 12.5% line that is shown to represent the CFD metric. CFD readings between 12.5% and 25% are classified as “acceptable.” This means that in the course of most human activities, the modulation will rarely be perceptible. CFD readings from 25% to 50% are classified as "moderate" This means modulation may be perceived by some people under some circumstances and people may possibly experience discomfort after prolonged exposure, for example with increased eye strain at work. With CFD readings from 50% to 75%, the classification is "strongly affected". In this performance tier 50% of the population may either directly perceive flicker or notice stroboscopic effects. There is likely to be discomfort after prolonged exposure and such light is judged barely suitable for work. CFD readings of above 75% are classified as “extremely affected” meaning that flicker and/or stroboscopic effects will be noticed by more than 75% of the population. Prolonged exposure will lead to impaired physical condition (headache, feeling of general malaise) and there is risk of epileptic seizure. Such light quality is dangerous in workshops with rotating or reciprocating machinery, as mentioned in EN12464-1.

AC LED LIGHT ENGINES AND FLICKER

There exist on the market numerous AC LED light engines which use arrays of high voltage solid state switches to automatically connect and disconnect LEDS in the light engine from the power line. The resulting light output goes to zero at the line voltage zero crossing. This produces a modulation at twice the power line frequency which some people can detect. For example, the light source for the moving pencil in Fig.2 was from such a light engine. The light signature from such a light engine is shown in Fig.5. This kind of commonplace light engine is characterized by a flicker index of 0.34 and a CFD rating of 53%. For this reason the lighting specifier community has been reluctant to specify these light sources for major installations, despite the fact that they are cost effective and easy to assemble into luminaires. If the light quality from driverless AC light engines was comparable to that from an incandescent light bulb, then a large fraction of LED luminaires would probably already be using AC LED light engines. When light signatures from all the available driverless light engines are compared, a notable exception is the light signatures from the AC light engine products of ERG lighting in Endicott, New York. These light engines use Photalume technology. The light signature from one of these is shown in Fig.6.

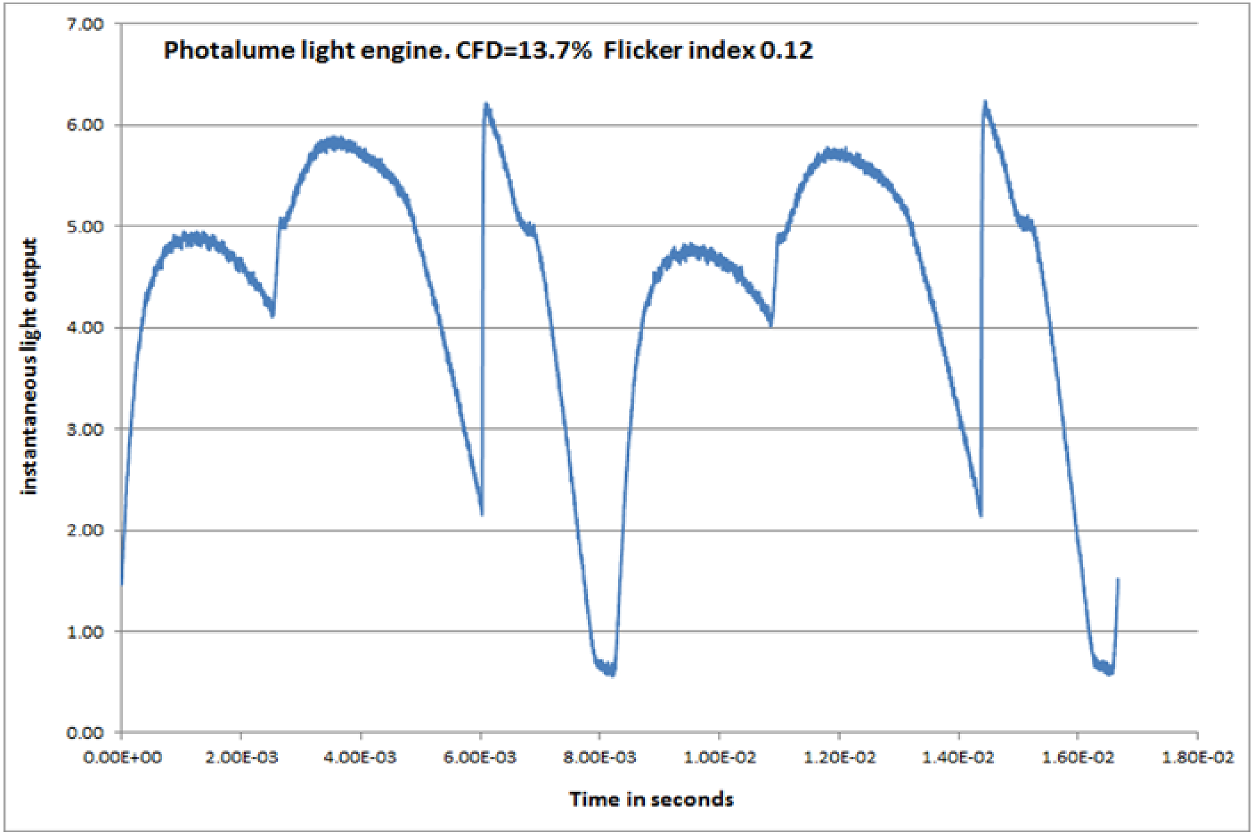

Figure 6. Light signature of a Photalume light engine

By the older non frequency sensitive criteria of flicker index it already scores low, with a flicker index of 0.12, compared to 0.34 for the older traditional AC LED light engines. Using the CFD tool which takes frequencies up to 2000 Hz into account, it has a CFD rating of 13.7%, compared to 53% for a conventional AC LED light engine or 6.9% for a 230V incandescent light bulb. A magnetic ballasted fluorescent lamp has a CFD rating of 20%. Thus the light engine from ERG scores dramatically better in flicker performance, being 1.5X better than a magnetic ballasted fluorescent tube and 3.8X better than a conventional driverless AC LED light engine. These ERG light engines have been previously described in LEDs magazine. (8). They are characterized by storing up small amounts of electrical energy and then using it to generate light pulses at a rate of around 6 pulses per power line cycle, i.e. 270-360 Hz for a 60 cycle power line. These frequencies are completely invisible to the human eye. New products in preparation are reported to have flicker performance which is about 30% better.

CONCLUSIONS

Previous attempts to provide a metric for characterizing the acceptability of light with high frequency fluctuations have been limited by only taking account of directly visible light fluctuation frequencies. There exists well documented research showing that human visual performance is impaired in the presence of higher frequency, not directly visible, fluctuations. The new CFD metric from Der Lichtpeter extends the techniques previously described by the Lighting Research Center from a maximum of 100 Hz bandwidth up to and beyond 2000 Hz bandwidth. Any arbitrarily shaped light signatures can be analyzed. The results of applying this new metric to AC LED light engines give a dramatic new insight with respect to the performance of light engines that use higher frequencies for modulation of the light. Specifically some of these light engines were 2X superior to the old 120 Hz light engines on the old, non-frequency sensitive metric of flicker index. Evaluated with the new CFD index, these higher frequency light engines show up to be 4X superior when frequency of modulation is taken into account, performing with flicker properties in a range comparable to incandescent light bulbs.

An executable file to perform the CFD analysis of light signatures on one Windows computer can be downloaded free of charge from the Der Lichtpeter website, in return for identification. This software can also detail other standard indexes, such as the flicker index and the percentage flicker.

The Photalume technology uses US patent 9,491,821 and US patent application 20160100464 (now allowed.) Licenses to use this technology can be obtained from Photalume.

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