Light Flicker: A Reasonable Measurement Method in View

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Abstract— **Meanwhile, there are some measuring devices to measure light flicker because it has been recognized that fluctuations in the brightness of artificial illumination have a negative effect on the nervous system of humans and other beings. Despite the years after recognizing the need to measure this, there is still no agreement on the measurement method. The only thing that is clear is that a simple amplitude measurement is not enough, but that an analysis and a weighted evaluation of the individual frequencies over a wide range is the right approach. According to this, many of the measuring methods, presented in the meantime worldwide, are not suitable to the compatibility with humans. In fact there are basically only two methods left:**

- **Compact Flicker Degree CFD**
- **TLA combining PstLM and SVM**

I. Light flicker measuring methods

Inappropriate methods are either those operating in the time domain where no frequencies are taken into account at all, or those though operating in the frequency domain, but where the frequency range is insufficient or where there are definition gaps or discontinuities in the frequency range.

A. Unsuitable methods

The most widespread method according to **IES: RP-16-10** [1] with %flicker (pure amplitude ratios) and flicker index (pure area ratios) is the least suitable method because two values whose combination is not defined are not communicable and also frequencies are not considered at all.
IEEE 1789 [8] only considers the main frequency and the sensitivity functions contain physiologically unexplained discontinuities. In addition, the limits are so sharp that even the low flicker of the European incandescent light bulb is considered dangerous.
The procedure according to California Energy Commission **CEC Title 24 JA10** [5] fails due to the lack of weighting of contained frequencies, which is why a highly noticeable flicker below 25 Hz is considered "low flicker".
The procedure according to **ASSIST** [2] includes only frequencies up to 70 Hz, thus stroboscopic and phantom array effects are not taken into account.
For the above methods have been analysed within the process for the new European Eco-Design Directive and there considered not suitable [11], they are not discussed in the further course.

B. Remaining methods

The Compact Flicker Degree (**CFD**) [6][7] continues to be the template for a way to measure, declare and assess light flicker, because the method provides a single percentage value for the entire frequency range effecting on humans with frequency-dependent weighting and without definition gaps or discontinuities.
CIE describes light flicker with the term "Temporal Light Artefact" (**TLA**) [3][4] and proposes the IEC **PstLM** method, which though is not sufficient due to its low cut off frequency. Referred to NEMA 77: 2017 this is supplemented by the CIE **SVM** procedure [12]. The resulting two values for the measurement of light flicker make the communication difficult and a normative setting of application-specific limit values is practically impossible.
This paper deals with the suggestion of a validated smart combination of both values into one, which would make the TLA measurement useful.
In order to complete the discussion on the effects of light modulation, this paper also shows that an additional measurement method for the phantom array effect is superfluous.

The two remaining methods CFD and TLA are up for discussion for the new European Eco-Design Directive and for standardisation by the IEC.

II. Measuring of the phantom array effect not needed

The phantom array effect (ghosting) is caused by stroboscopic light. The difference is the perspective of the observer: Watching a relatively small light source from a distance with fast eye movements or at different speed to the observer the light appears to be an array of light points. Examples of this are the daytime running lights and rear lights of motor vehicles which lead to irritation [9][10].
So a distinction between the "stroboscopic effect" and the "phantom array effect" may be useful for explanatory purposes. However, for the evaluation of a light source, the assessment and for limit values, there must be no difference for the following reasons:

Imagine the position of an observer standing directly under a street lamp. The street lamp emits its light with 100 Hz rectangle with a duty cycle of 50%. The observer experiences stroboscope light. Now the observer slowly moves away from this lamp (about 300 yards), so that in this bigger distance the light of the street lamp appears to the observer as a small light source. If the observer now quickly moves his eyes (saccades), then he experiences the phantom array effect of this lamp. During the walk away from the lamp, depending on the distance of the observer from the lamp, each intermediate state between stroboscope light and phantom array effect is possible and thus the light is experienced as a mixture of both.

Additionally: While the cause of "phantom array effect" is stroboscopic light with high contrast containing dark periods of time, the modulation is always above 80%. Consequently it is very unlikely to perceive this effect with a light modulation of 10% (according to CIE [3]). If that was so, even the European incandescent bulb would have become a case of ghosting, which has never been reported.

In contrast to the perception of the stroboscopic effect or even light flicker of lower frequency, the perception of the phantom array effect depends less on the frequency of the light. The perceptibility of the phantom array effect is mostly dependent on the light frequency in so far as the higher the frequency, the eye movements must be faster in order to perceive this effect at all.

By looking into the modulation versus frequency chart (sensitivity), the phantom array effect curve may be moved upwards by a factor of only 2.5. This brings it out of the 10% modulation range and makes it similar to the SVM curve. As a result the measuring method of the phantom array effect is covered by the SVM method.

Thus the phantom array effect curve becomes superfluous.

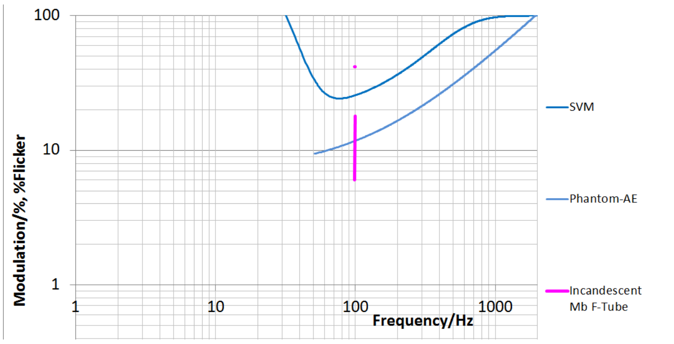

Fig. 1. Sensitivity curve of the phantom array effect

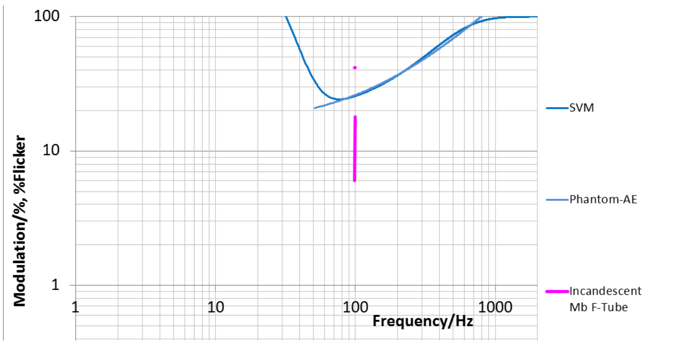

Fig. 2. Sensitivity curve of the phantom array effect assimilated by SVM

III. Calculations in Frequency Domain

For the two remaining methods the calculation in the frequency domain is required.

It has to be emphasized that the method of the frequency analysis has a decisive effect on the result for CFD, PstLM and SVM. Neglecting this aspect might lead to a result error of up to 20% of the final value, because of the high dynamic in the weighting curve. In order to minimize errors in the summation of the frequency components, the spectral leakage should be absent.

The spectral leakage in continuous-time signal analysis is based on the fact that in reality every signal has a beginning and an end and cannot be continued periodically for an infinite time. The effects of the spectral leakage can be minimized by using appropriate methods such as the use of special windowing filter functions. Depending on the selected window function, this can be virtually completely eliminated in a further operation of the signal analysis.

Requirements for the complete elimination of spectral leakage:

- Signals are examined which contain predominantly periodic signals, which mainly contain a fundamental frequency and associated harmonics.
- A window function is selected whose spectral leakage error is predictable.
- The significant spectral leakage fraction of the window function is limited to a few bins.

The first condition is given in the context of the investigation of the residual ripple of artificial, electrical light sources (light modulation). The modulation components in the signal are usually generated by the infeed (mainly mains voltage) or the internal electronics (e.g. PWM). It may be allowed to assume that noise signals are almost absent, which in turn can be completely eliminated by a downstream noise filter. The second condition is met when a window function is selected which provides an FFT analysis for a signal jump to 1 for the entire signal. The step response is usually a falling, running towards zero curve.

Investigations have shown that the window functions Blackman-3T, Blackman-Nuttall, and Hann are best. This is because the spectral leakage is significantly limited to a few bins and is therefore predictable and can be completely eliminated.

Light modulation calculations performed by Der Lichtpeter fully apply appropriate methods.

IV. CFD METHOD

The Compact Flicker Degree CFD [11] is defined by a single percentage as the final value by calculating the Pythagorean Sum (Euclidean norm or Vector-p-norm with p=2) on the single weighted frequencies.

$$CFD = \sqrt[2]{\sum_{i=1}^{N} \left(\frac{C_i}{T_i}\right)^2} \quad (1)$$

where Ci is the normalized amplitude of the i-th Fourier component and Ti is the CFD sensitivity value for the effect for a sine wave at the frequency of the i-th Fourier component. N is limited by the number of samples only.

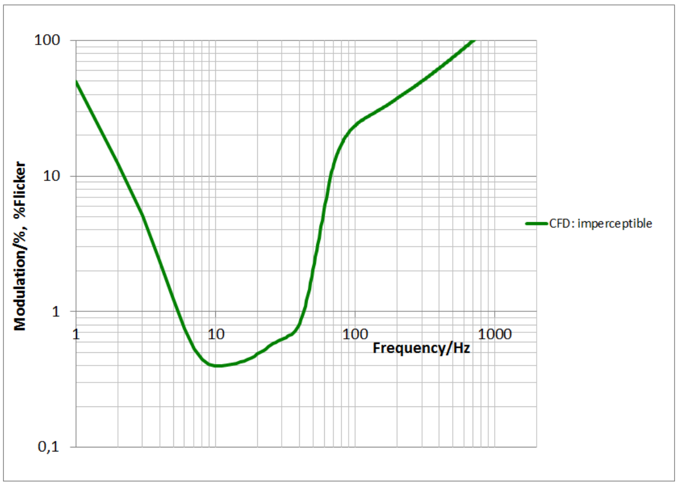

Fig. 3. CFD sensitivity curve

All frequencies for visible and invisible temporal changes in brightness are included in the calculation. The range below 10 Hz is weighted lower to avoid the over-estimation of remaining FFT leakage effects occurring in practice.
For dimmable light sources, the measurement is performed 1_{st} with 100% brightness and 2_{nd} with 25% brightness, the worse of both values is declared as the final value.

The transition from the non-linear frequency range up to about 70 Hz, which is perceptible when situated rested, into the range which is rather perceptible under motion, the CFD performs this as smooth (physiologically plausible).

The CFD given in a single percentage as a comprehensive measurand for modulated light is suitable for declaration and permits categorization according to a traffic light system. The categorization criteria for the CFD depend both on the visibility and on the relevance and risk in the respective application. For example, in a workshop it is essential to avoid stroboscopic effects for the safe operation of rotating machines, whereas they play a little role in walkways, parking lots or storage spaces.

V. COMBINATION OF PSTLM AND SVM

In order to obtain one single measuring value for TLA without any discontinuity at 60..70 Hz, the two single values for PstLM and SVM have to be merged somehow. The test method and data analysis for the IEC Pst is time domain based and contains statistical calculations whereas the CIE SVM is frequency domain based, which are two very different measuring methods. This would create some complexity in approaches to testing with the development of a modified and calibrated flicker meter required for the IEC part.

So the smart basic idea is to harmonize respectively to convert the IEC Pst calculation method into a PstLM method by operating in frequency domain and by using the same formulas as for the SVM method, but with different weighting characteristics. As it is possible to represent the PstLM curve in the same chart as the SVM curve, it should be possible to use the frequency response as the sensitivity curve.

A. *Converting the Pst_{IEC} = 1.0 into a Pst_{LM} sensitivity curve*

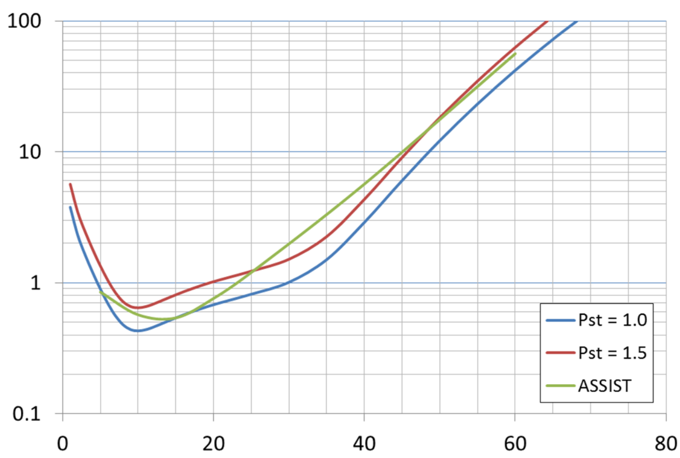

Fig. 4. Sensitivity curve Pst=1.0

The mathematical polynomial function, determined from the sensitivity curve Pst=1.0 ([13], page 26) in the modulation versus frequency chart, will be called $Mod_{Pst=1.0}(f)$ below.

B. *Calculating PstLM with the sensitivity $Mod_{Pst=1.0}(f)$*

The calculation method is applied in the same manner as for CIE SVM[4]:

$$PstLM = \sqrt[3.7]{\sum_{i=1}^{N(\leq 2kHz)} \left(\frac{C_i}{T_i}\right)^{3.7}} \quad (2)$$

where Ci is the normalized amplitude of the i-th Fourier component and Ti is the PstLM sensitivity value $Mod_{Pst=1.0}(f)$ for the effect for a sine wave at the frequency of the i-th Fourier component.

C. Verifying harmonized PstLM against IEC Pst

The method has been verified by calculating 18 different waveforms in flicker frequency range (below 70 Hz) against a reference flicker meter. The deviation is $\leq 3\%$.

D. Combining the sensitivity curves of PstLM and SVM

After the calculation method for PstLM has been verified, it is now possible to combine the sensitivity values for each frequency by merging each single value $T_{PstLM}(f)$ and $T_{SVM}(f)$ using the vector-p-norm inversely proportional. p has been chosen 1.5 to get the best compromise between modifying the two single sensitivity curves as little as possible and closing the discontinuity gap by a steadily rising piece (according to the humans sensitivity decreasing with higher frequency).

$$T_{TLA}(f) = \sqrt[-1.5]{T_{PstLM}(f)^{-1.5} + T_{SVM}(f)^{-1.5}} \quad (3)$$

where $T_{SVM}(f)$ is the sensitivity for SVM according to CIE TN 006:2016 [3] and $T_{PstLM}(f)$ is the PstLM sensitivity $Mod_{Pst=1.0}(f)$ from above.

This merging method results in the following sensitivity curve:

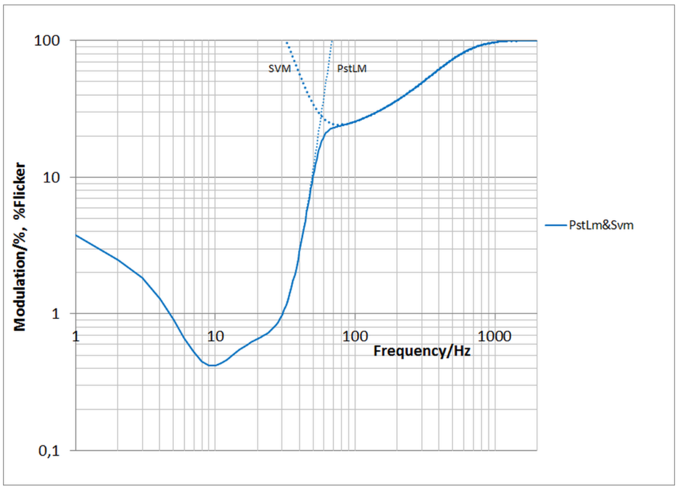

Fig. 5. Sensitivity curve of PstLM merged with SVM

E. Calculating TLA with the combined sensitivity

The calculation method is again the same as for CIE SVM:

$$TLA = \sqrt[3.7]{\sum_{i=1}^{N(\leq 2kHz)} \left(\frac{C_i}{T_i}\right)^{3.7}} \quad (4)$$

where Ci is the normalized amplitude of the i-th Fourier component and Ti is the combined sensitivity value $T_{TLA}(f)$ for the effect for a sine wave at the frequency of the i-th Fourier component.

VI. Overview including the CFD

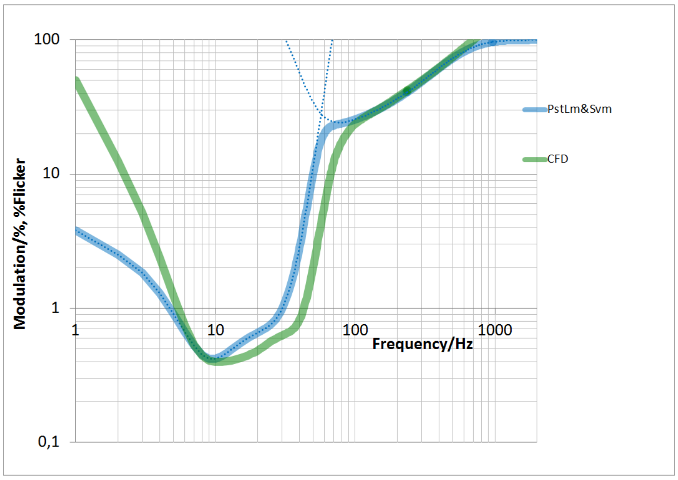

Fig. 6. Sensitivity curves of TLA (PstLM&SVM) and CFD

The PstLM&SVM curve now comprises the single values for PstLM as the replacement for IEC Pst, SVM and also phantom array effect, for the latter has been assimilated by SVM and thus regarded to be superfluous as an extra value.

One can see now, that PstLM&SVM curve and the CFD curve are not very far away from each other.

Nevertheless the TLA calculation using the vector-p-norm with p=3.7 has the advantage to be more tolerant of spectral leakage evoked by FFT using window functions. On the other hand a high p value tends to rate mainly the fundamental frequency and thus neglects the waveform much more than the CFD calculation method does with p=2 [11].

VII. EXAMPLE

This example shows a light signal in a chart including other known sensitivity curves.

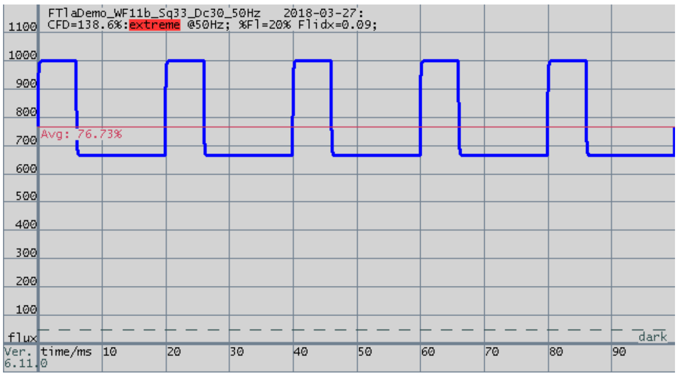

Fig. 7. Signal: Square, 50 Hz, DC=30%, MD=20%

FFT analysis (normalized to DC=1.0):
@50 Hz: 0.1123 (-18.99 dB; MD=22.46%) *
@100 Hz: 0.0655 (-23.68 dB; MD=13.1%) *
@150 Hz: 0.0134 (-37.44 dB; MD=2.68%)
@200 Hz: 0.0209 (-33.59 dB; MD=4.18%)
@250 Hz: 0.0276 (-31.18 dB; MD=5.52%)
@300 Hz: 0.0129 (-37.82 dB; MD=2.58%)
@400 Hz: 0.0166 (-35.59 dB; MD=3.32%)
@450 Hz: 0.0119 (-38.49 dB; MD=2.38%)
(*) Values displayed in next graphic (fig. 8)

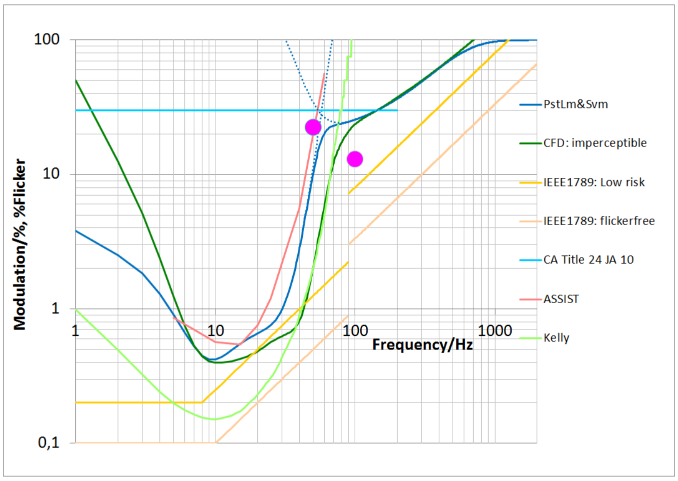

Fig. 8. CFD = 139% PstLM = 1.85; SVM = 0.72; PstLM&SVM = 2.11

VIII. OTHER ASPECTS

Whether dimming by leading edge, trailing edge or PWM (also spread spectrum): The final value can be obtained by either performing several measurements in the dimmed state or a single measurement at given brightness (50% or 25% as with the CFD) and drawing on the worst value.

Control gears may be tested separately in conjunction with a load the DUT is specified for.

Test against mains flicker may be enhanced by stimulating the DUT. Thus for example by adding a rectangular wave shape with 20 Hz or 8.8 Hz modulated with 0.5%. The limitation value should be based on the behaviour of a 60W incandescent bulb.

In addition to the visible effects, temporal modulations of light can also cause adverse interference with technical equipment. Known examples include striped image interference in any cameras in cases where the shot object is illuminated with stroboscopic light caused by PWM-dimmed LED systems or LED driver systems working without capacitors. Other disturbances may occur with barcode readers, pulse oximeters, sensors, optical measurement laboratories, light barriers etc.
These special cases should be treated separately or in general stroboscopic light of any frequency should be avoided or light modulation should be minimized accordingly.

Apart from all this, as humans we should not forget other sentient beings on earth like birds, nocturnal animals. Therefore general limitations should be set to MD $\leq$50%, TLA $\leq$1.5, CFD $\leq$25%.

IX. CONCLUSIONS

It is necessary to measure and assess light for illumination or static information purposes with respect to all modulations affecting humans and other beings. For this all frequency components should be considered at least up to 2 kHz, better up to 20 kHz. Consequently, the calculation is possible only in the frequency domain, whereby at best each individual frequency is weighted according to the influence on the human being. According to human perception, the weighting curve does not contain any definition gaps or discontinuities. For the declaration in the technical data or on the packaging, a single measurement is best suited. Several measurements for the same annoyance - the effect of light modulation on humans - are poorly communicable. In addition, the use of a single measure also makes it clearly easier to define normative application-dependent limit values.

As presented in this paper only the Compact Flicker Degree CFD and TLA as a combination of PstLM and SVM fulfill these requirements.

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