Measuring What’s Hard to Describe: The Latest Research on “Flicker”
April 27, 2016  4:30-6:00pm
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Agenda

• Introduction: What is Flicker and TLA?
• Challenges of measurement metrics
• New industry efforts
• Where do we go from here?
Introduction and Background
**Definition: Temporal Light Artifacts (TLA)**

**Flicker**
Perception of visual unsteadiness induced by a light stimulus whose luminance or spectral distribution fluctuates with time, for a static observer in a static environment.

\[ \text{~0-80Hz} \]

**Phantom Array**
Perception of a spatially extended series of light spots when making a *saccade* (image transition across the retina) across a light source that fluctuates with time.

\[ \text{~50Hz-2kHz} \]

**Stroboscopic Effects**
Change in motion perception induced by a light stimulus whose luminance or spectral distribution fluctuates with time, for a static observer in a non-static environment.

\[ \text{~50Hz-2kHz} \]
Definition: Temporal Light Artifacts (TLA)

**Temporal Light Artifact (TLA)**
An undesired change in visual perception, induced by a light stimulus whose luminance or spectral distribution fluctuates with time, for an observer in a certain environment.
Why is TLA bad?

- May cause eye strain or headaches
- May impair visual or cognitive performance
- Distracting
- May trigger medical conditions *(in severe cases)*
- Interferes with optical equipment (cameras, etc.)
- **Could slow adoption of LED lighting due to perceived poor performance**

![Diagram showing severity levels: Mild, Harmful, Severe, Catastrophic]

- Photosensitive Epilepsy
- Stroboscopic Effect
- Migraine
- Aggravated Autistic Behavior
- Performance and Asthenopic or Eye Strain
Not all TLA is bad!

• Sunlight through trees
• Reflections off of water
• Motion pictures
• Emergency vehicles
• Attention-getting signage
• Entertainment

(Although TLA in general lighting probably is bad...)
Why do LEDs flicker?

- They don’t! *(inherently)*...
- They faithfully reproduce light based on the amount of current flowing through them.
Why do LEDs flicker?

• An LED driver’s job is to regulate current to the LEDs
  – Simpler drivers have a harder time avoiding current fluctuation, and are more prone to causing flicker
  – Voltage changes to the input of the driver (power line or control noise) can cause changes to the output
Why do LEDs flicker?

- LEDs respond QUICKLY to changes in current
  - No intrinsic filtering (unlike incandescent)
Sources of TLA

1. Source voltage changes (noise)
2. Externally coupled noise sources
3. Dimmer phase angle instabilities (when dimming)
4. Driver instabilities
5. Driver (intended) operation
Current state-of-the-art in TLA measurement

• Today’s best equipment for measuring flicker:

Unfortunately, results may vary due to:
• Age
• Visual acuity
• Fatigue
• Ambient light
• Experience
• Viewing angle
• Brightness...

Flicker is best perceived off of a reflected surface, not directly viewing the source.
Current flicker metrics

- Simple
  - Percent Flicker
  - Flicker Index

- Complex
  - RPI LRC ASSIST
  - IEC PST
  - SVM
  - IEEE
Percent Flicker (or % Modulation, or Modulation Depth)

- Easy to understand
- Easy to calculate
- Assumes periodic waveform
- Does not account for wave shape
- Does not account for frequency

\[ PF = 100\% \times \frac{A - B}{A + B} \]

No relation to human perception!
Flicker Index

- Easy to understand
- Assumes periodic waveform
- Does not account for frequency

\[ FI = \frac{\text{Area 1}}{\text{Area 1} + \text{Area 2}} \]

No relation to human perception!
Frequency independence

- Both graphs have same Flicker Index and Percent Flicker:
  - Same maximum
  - Same average
  - Same minimum
  - Same areas
- They will appear very different to an observer
  - 1Hz vs. 10Hz?
  - 10Hz vs. 100Hz?
**Uses of Flicker Index and Percent Flicker**

- Poor indicator of perceivable flicker
  - But, could be used to compare lamps with similar characteristics (operating frequency)

- Energy Star Lamps specification
  - Values are to be reported only; no limit

- California Title 24 Joint Appendix (JA) 8
  - Percent Flicker must be <30% at <200Hz
Better ways to measure TLA

1. Examine frequency components
2. Determine which frequencies are of interest (and how “interesting” they are)
3. Sum the result together
4. Compare that against a baseline or standard
1. Examine frequency components

- Most “real” waveforms (light, sound, etc.) can be mathematically represented by a combination of several simpler (sinusoid) waveforms
  - Like a chord is a combination of musical notes
- The mathematical operation to determine these source waveforms is the *Fast Fourier Transform* (FFT)
2. Determine interesting frequencies

- Remove (filter) frequencies that are irrelevant
  - For example, those above human perception
- Add a weighting factor to remaining frequencies

Frequency components <200Hz

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Signal weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>50Hz and 120Hz</td>
<td>Apply weighing</td>
</tr>
</tbody>
</table>

Result

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequencies we care most about</td>
<td></td>
</tr>
<tr>
<td>Frequencies we care least about</td>
<td></td>
</tr>
</tbody>
</table>
3. Add result together

- Normalize and perform a summation algorithm over the resulting (weighted) frequencies
  - Sum-of-squares, etc.

- Result is an integer value
4. Compare result against a standard

- Is lower or higher “better”?
- What’s an acceptable range?
- Does it vary based on application?
RPI LRC ASSIST metric

• Accounts for wave shape and frequency
• Based off of (limited) human perception trials
• Focuses on perceptible flicker: <100Hz
• Complex measurement and analysis:

Source: http://www.lrc.rpi.edu/programs/solidstate/assist/recommends/flicker.asp
RPI LRC ASSIST weighting curve
IEC flicker testing ($P_{st}$)

- IEC 61000-4-15
  - “Flickermeter – Functional and design specifications”
- IEC 61000-3-3
  - “Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems”
- IEC TR 61547-1 (Adopts IEC 61000 for use with light)
- Complex; originally developed to quantify power line quality

Structure of the IEC light flickermeter

Sources: https://webstore.iec.ch/publication/4150, https://webstore.iec.ch/publication/4173
IEC PST result curve

Modulation Depth

Frequency

- Blue line: $P_{st} = 1.0$
- Red line: $P_{st} = 1.5$
- Green line: ASSIST
Stroboscopic Visibility Measure (SVM)

- Measures primarily stroboscopic effects >80Hz (for moving objects), not necessarily static flicker
- Not yet well known or widely used in industry
- Based off of human perception trials

Source: Modeling the visibility of the stroboscopic effect occurring in temporally modulated light systems
http://lrt.sagepub.com/content/early/2014/05/12/1477153514534945.full.pdf?ijkey=GcQ3UW7Qz2UwqtM&keytype=ref
IEEE 1789-2015

• “IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers”¹

• Results drawn from multiple studies

• Results were somewhat controversial²

IEEE 1789-2015 and common sources

Source: IEEE Std 1789-2015, Figure 18 “Low Risk Level and No Observable Effect Level”
Comparison of several TLA metric limits

- Magnetically Ballasted HPS
- Magnetically Ballasted Fluorescent
- CA Title 24 proposed limit
- Incandescent
- IEEE 1789 Low Risk
- IEEE 1789 No Effect
- Electronically Ballasted Fluorescent
- Flicker
- Stroboscopic Effect

Modulation (%) vs. Frequency (Hz)
Challenges of measurement metrics
Measurement nuances: Equipment

- Spectral response of sensor
- Bandwidth and linearity of sensor
- Sampling frequency of recording device
- Vertical resolution of measurement

An algorithm is only as accurate as the data provided to it!

*(Garbage in...garbage out)*
Spectral response of sensor

  – (Should respond to the same frequencies of light in the same manner as the human eye)

![Graph showing the spectral response of green and red sensors](image)

**Green:** photopic human eye response curve

**Red:** typical photodiode
Bandwidth of sensor

- If a sensor has intrinsic filtering (by design or otherwise), it may ignore higher-frequency signals.
- Common light meters or commodity devices may only measure signals at a few hundred Hz (or less).
- Bandwidth that is TOO high may pick up undesired noise.

Source: https://en.wikipedia.org/wiki/Aliasing
Sampling frequency of recording device

• Energy Star: “The equipment sampling rate used shall be $\geq 2$ kHz [samples per second].”

• Minimum: sampling frequency must be 2x the maximum frequency of interest (Nyquist rate)
  – Better: sampling frequency should be 10x the maximum frequency of interest

• Sampling that is too slow distorts the measurement of the signal and can miss higher-frequency components
  – Sample frequency is one of the differences between analog phone-quality and CD-quality audio
Resolution of measurement

• Typical oscilloscopes have only 8 bits of resolution
• For very small signals, data gets steppy (quantized)

9 bits (512 steps) of vertical resolution
8 bits (256 steps) of vertical resolution
7 bits (128 steps) of vertical resolution

(Constant horizontal resolution)

Loss of data
Resolution of measurement

- Undesirably-quantized data can be seen on a light level graph
- This indicates the amplitude of the signal should be increased and retested

No light levels were recorded between the red lines... very unlikely!
Measurement nuances: Test conditions

- Power source
- Mechanical stability
- Ambient light
- Sample length
- Stabilization
Power source

• Power sources that are “too perfect” (inverters, power supplies) may mask poor real-world behavior

• Normal building power may have specific noise sources (motors, elevators) that are impossible to duplicate

• An ideal source reliably and repeatedly reproduces common noise; for example:

\[ y(t) = 120 \times \sqrt{2} \times \sin(2 \times \pi \times 60 \times t) + 2.25 \times \sin(2 \times \pi \times 200 \times t) \]
Mechanical stability

- Mechanical vibrations may result in detected modulation of light (especially with light gradients)
- This can be coupled in from nearby equipment or even footsteps
- Test samples and measurement probes should be securely attached to the test chamber, and isolated from vibration
Ambient light

- External light sources can suppress or corrupt proper flicker measurement
- Measurements should be taken in a dark box
  - A total integrating sphere is unnecessary; relative light levels are sufficient
- Zero light = zero signal
Stabilization

- Lamps may behave differently during their first few seconds or minutes of operation
- When should the measurement be taken?
- How long should a user wait for stable light output?

*Light takes 25 seconds to become stable*
Sample length

• Energy Star: “The equipment measurement period shall be $\geq 100 \text{ ms}$”

• What if flicker is seen only every 2s? Every 20s?

• Large measurements at high resolution create large files
  – 20k samples/second * 60 seconds = 1.2M samples
  – Some equipment or software cannot handle such large files well (Excel)

Glitch occurs 20 seconds into measurement
New Industry Efforts
NEMA TLA work

• NEMA has a TLA working group developing a method of reproducible measurement focused on general purpose LED lighting

• Pass/fail limits can be set by external standards-setting bodies (such as IES) on an application-specific basis

• It will involve a digital measurement and mathematical frequency-based analysis
NEMA TLA scope

The purpose of the standard is:

1. Recommend a method of quantifying the visibility of temporal light artifacts (TLA), and
2. Propose application-dependent limits on TLA

The NEMA group will most likely propose initial application-dependent limits, which will later be refined by IES.
NEMA TLA results (so far)

- Data has been collected through a Round Robin study
  - 3 dimmer models
  - 7 light source models
  - Measure each combination, with no dimmer and at three different settings with dimmer
  - Note cases where TLA may have been observed

Summary from one manufacturer:

<table>
<thead>
<tr>
<th>Level</th>
<th>% Flicker</th>
<th>Flicker Index</th>
<th>LRC</th>
<th>SVM Metric</th>
<th>Pst Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>29.4</td>
<td>0.077</td>
<td>0.368</td>
<td>0.294</td>
<td>0.637</td>
</tr>
<tr>
<td>Medium</td>
<td>39.0</td>
<td>0.097</td>
<td>0.442</td>
<td>0.390</td>
<td>0.547</td>
</tr>
<tr>
<td>Low</td>
<td>30.0</td>
<td>0.075</td>
<td>0.576</td>
<td>0.300</td>
<td>1.028</td>
</tr>
</tbody>
</table>
Round Robin: Detailed look at one dimmer/lamp (SVM)

Each point measured 5 times.

Small amount of variation
Little dependence on input supply
Round Robin: Detailed look at one dimmer/lamp ($P_{st}$)

Each point measured 5 times.

Larger amount of variation
Dependence on input supply
NEMA TLA proposal (so far)

- A single value may not accurately capture all application-specific requirements
  - Some applications or users may be more sensitive to visible flicker (task-based work)
  - Some applications or users may require minimal stroboscopic flicker (video, motion-based work)
- A dual-value metric may be most suitable
NEMA TLA next steps

• When completed,
  – Compare results
  – Select metrics for manufacturers to report
• Create suggested limits on the metrics for different applications
• Transfer methodology to IES for detail on applications and associated limits
• Immediate interest in using NEMA TLA metric as part of a consumer dimming logo
DoE Flicker Characterization Study

• Report on the performance of commercially available flicker meters against a benchmark

• Purpose of the study:
  – Help specifiers determine the flicker behavior of lighting products
  – Accelerate the development of standard test and measurement procedures

• Published in February 2016

Source: http://energy.gov/eere/ssl/downloads/characterizing-photometric-flicker
DoE Flicker Characterization Study: Conclusions

1. “Lighting manufacturers and testing laboratories should start characterizing lighting products for flicker”

2. “When characterizing flicker, take measurements at full as well as one or more dimmed light levels”

3. “Lighting designers and specifiers might consider purchasing a handheld meter and starting to characterize the flicker”
   “[But] watch out for ambient light and other conditions that might result in the handheld meter not yielding as accurate a result”

4. “Follow IES, CIE, and NIST developments for flicker…”
   “…especially those that consider aperiodic waveform content, or allow weighting factors to be applied to specific frequencies of interest…”
Other Industry Efforts

• CIE working group: *TC 1-83: Visual Aspects of Time-Modulated Lighting Systems*¹

![CIE Logo](image)

• Third-party flicker testing services²

![UL Logo](image)

Sources: ¹ [http://div1.cie.co.at/?i_ca_id=549&pubid=466](http://div1.cie.co.at/?i_ca_id=549&pubid=466) ² [https://ul.com/newsroom/pressreleases/ul-launches-verification-service-for-low-optical-flicker/](https://ul.com/newsroom/pressreleases/ul-launches-verification-service-for-low-optical-flicker/)
Where do we go from here?
Recap: Characteristics of a good TLA metric

• Accounts for frequency
• Accounts for wave shape
• Covers visible and stroboscopic (non-visible) flicker
• Accounts for non-steady-state flicker
• Adaptable for different applications
• (Relatively) easy to measure, calculate, and understand
• Widely adopted

No one metric today meets all of these!
Standards adoption

- Some manufacturers are starting to cite IEEE-1789 in their product specifications:
  - Meets IEEE1789 recommendations over its entire dimming range, eliminating negative health effects related to flicker
  - PWM dimming meets IEEE1789.

- However, CA Title 24 is the only known US standard that mandates a flicker metric
Unintended consequences

- Adding stroboscopic measurements to flicker tests may cause otherwise “good” lamps to fail
  - *Most manufacturers’ visual tests today don’t account for stroboscopic flicker*
- Improper use of flicker metrics may mandate high-levels of performance, even when unnecessary
- Poor testing procedures may cause invalid results, or incorrectly attribute flicker to the control or driver
- Flicker tests may add to already-lengthy testing
Parting thoughts

• Should I be concerned about TLA?
  – Yes! It is a source of occupant discomfort and dissatisfaction

• Are there standards I should be citing for flicker?
  – Not yet! Current standards are either useless or overly stringent for most applications.

• How can I minimize chances of having flicker?
  – Work with quality manufacturers
  – Realize that low cost often correlates with less filtering (and more TLA)
  – Spec digital control schemes over analog ones

• Stay tuned for further developments!
Demonstration invitation

• Where do you see flicker?
• Where do you see stroboscopic effect?
• What’s visible to your naked eye vs. a camera?
• Shows effects of frequency, wave shape, modulation depth, and duty cycle on TLA visibility
Please remember to complete the course evaluations. Thank you.