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TECHNICAL REPORT

Visual Aspects of Time-Modulated Lighting Systems

CIE 249:2022

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159.931

Descriptor: Physiological optics. vision
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This Technical Report has been prepared by CIE Technical Committee 1-83 of Division 1 "Vision and Colour" and has been approved by the Board of Administration and Division 1 of the Commission Internationale de l'Eclairage. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

Ce rapport technique a été élaboré par le Comité Technique (TC) 1-83 de la CIE Division 1 "Vision et Couleur" et a été approuvé par le Bureau et Division 1 de la Commission Internationale de l'Eclairage. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire.

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VISUAL ASPECTS OF TIME-MODULATED LIGHTING SYSTEMS

Summary

The fast rate at which solid-state light sources can change their luminous output is one of the main drivers behind the revolution in the lighting industry and applications of lighting. The fast rate of the intensity change means that a modulation of the luminous output, both intended and unintended, is directly linked to the modulation of the driving current. In turn, the light modulation can give rise to distortions in the perception of the environment. While in some very specific entertainment applications a distorted perception due to light modulation is desired, for most everyday applications and activities the distortion is detrimental and undesired. These changes in the perception of the environment are called "temporal light artefacts" (TLAs) and can have a large influence on the experience of the illumination quality. Moreover, studies indicate that exposure to light exhibiting visible and measurable temporal modulation can lead to a decrease in performance, increased fatigue as well as acute health problems like migraine episodes.

The potential negative effect of temporal light artefacts has prompted lighting manufacturers, lighting application specialists, universities and governments to look for ways to measure the effect and come to a better understanding of the temporal quality aspects of lighting systems. In this context, the CIE established Technical Committee (TC) 1-83 "Visual Aspects of Time-Modulated Lighting Systems".

In 2016 the CIE published the first output of TC 1-83, Technical Note (TN) 006:2016 "Visual Aspects of Time-Modulated Lighting Systems – Definitions and Measurement Models". This Technical Report builds on this previously published TN. In the first part of this document, the definitions for the perceptual effects that modulated light can produce are given. In the second part, an overview of the relevant literature is given as well as an overview of the parameters that influence the visibility of the different TLAs. The next part gives a description of two methods, one in the frequency domain and one in the time domain, which can be used to quantify visibility of TLAs. Three different implementations of these methods into specific visibility measures are given as an example. In the following part practical guidelines are outlined on how to test light sources. Finally, recommendations are provided on the use of the definitions and quantification methods, together with directions for future work.

ASPECTS VISUELS DES SYSTÈMES D'ÉCLAIRAGE À MODULATION TEMPORELLE

Résumé

La rapidité avec laquelle les sources lumineuses à semi-conducteurs peuvent modifier leur rendement lumineux est l'un des principaux moteurs de la révolution de l'industrie de l'éclairage et des applications de l'éclairage. La rapidité du changement d'intensité signifie qu'une modulation du flux lumineux, intentionnelle ou non, est directement liée à la modulation du courant d'attaque. À son tour, la modulation de la lumière peut donner lieu à des distorsions dans la perception de l'environnement. Alors que dans certaines applications de divertissement très spécifiques, une perception déformée due à la modulation de la lumière est souhaitée, pour la plupart des applications et activités quotidiennes, la distorsion est préjudiciable et indésirable. Ces changements dans la perception de l'environnement sont appelés "artefacts lumineux temporels" (TLA) et peuvent avoir une grande influence sur l'expérience de la qualité de l'éclairage. En outre, des études indiquent que l'exposition à une lumière présentant une modulation temporelle, visible et mesurable, peut entraîner une diminution des performances, une augmentation de la fatigue ainsi que des problèmes de santé aigus tels que des épisodes de migraine.

L'effet négatif potentiel des artefacts lumineux temporels a incité les fabricants d'éclairage, les spécialistes des applications d'éclairage, les universités et les gouvernements à chercher des moyens de mesurer cet effet et de mieux comprendre les aspects de la qualité temporelle des systèmes d'éclairage. Dans ce contexte, la CIE a créé le comité technique (TC) 1-83 "Aspects visuels des systèmes d'éclairage à modulation temporelle".

En 2016, le TC a publié la note technique (TN) 006:2016 "Aspects visuels des systèmes d'éclairage modulés dans le temps - Définitions et modèles de mesure". Le présent rapport technique s'appuie sur cette TN précédemment publiée. Dans la première partie de ce document, les définitions des effets perceptifs que la lumière modulée peut produire sont données. La deuxième partie donne un aperçu de la littérature pertinente ainsi qu'un aperçu des paramètres qui influencent la visibilité des différents TLA. La partie suivante donne une description de deux méthodes, l'une dans le domaine fréquentiel et l'autre dans le domaine temporel, qui peuvent être utilisées pour quantifier la visibilité des TLAs. Trois implémentations différentes de ces méthodes dans des mesures de visibilité spécifiques sont données à titre d'exemple. La partie suivante présente des directives pratiques sur la manière de tester les sources lumineuses. Enfin, des recommandations sont fournies sur l'utilisation des définitions et des méthodes de quantification, ainsi que des orientations pour les travaux futurs.

VISUELLE ASPEKTE VON ZEITMODULIERTEN BELEUCHTUNGSSYSTEMEN

Zusammenfassung

Die schnelle Frequenz, mit der Festkörperlichtquellen ihre Lichtleistung ändern können, ist einer der Haupttreiber hinter der Revolution in der Beleuchtungsindustrie und Beleuchtungsanwendungen. Die schnelle Frequenz der Intensitätsänderung bedeutet, dass eine Modulation der Lichtleistung, sowohl beabsichtigt als auch unbeabsichtigt, direkt mit der Modulation des Treiberstroms verbunden ist. Die Lichtmodulation kann wiederum zu Verzerrungen in der Wahrnehmung der Umgebung führen. Während in einigen sehr speziellen Unterhaltungsanwendungen eine verzerrte Wahrnehmung aufgrund von Lichtmodulation erwünscht ist, ist die Verzerrung für die meisten alltäglichen Anwendungen und Aktivitäten schädlich und unerwünscht. Die Veränderungen in der Wahrnehmung der Umgebung werden als "temporale Lichtartefakte" (TLA) bezeichnet und können einen großen Einfluss auf das Erleben der Beleuchtungsqualität haben. Darüber hinaus deuten Studien darauf hin, dass die Exposition gegenüber Licht, das eine sichtbare und messbare zeitliche Modulation aufweist, zu einem Leistungsabfall, erhöhter Müdigkeit sowie zu akuten gesundheitlichen Problemen wie Migräneanfällen führen kann.

Die potenziellen negativen Auswirkungen von temporalen Lichtartefakten haben Beleuchtungshersteller, Beleuchtungsanwendungsspezialisten, Universitäten und Regierungen dazu veranlasst, nach Möglichkeiten zu suchen, die Auswirkungen zu messen und zu einem besseren Verständnis der temporalen Qualitätsaspekte von Beleuchtungssystemen zu gelangen. In diesem Zusammenhang gründete die CIE das Technische Komitee (TC) 1-83 "Visual Aspects of Time-Modulated Lighting Systems".

Im Jahr 2016 veröffentlichte das TC die Technical Note (TN) 006:2016 "Visual Aspects of Time-Modulated Lighting Systems – Definitions and Measurement Models". Der vorliegende Technische Bericht baut auf dieser zuvor veröffentlichten TN auf. Im ersten Teil dieses Technischen Berichts werden neue Definitionen für die Wahrnehmungseffekte, die moduliertes Licht erzeugen kann, gegeben. Im zweiten Teil wird ein Überblick über die relevante Literatur gegeben sowie eine Übersicht über die Parameter, die die Sichtbarkeit der verschiedenen TLAs beeinflussen. Im nächsten Teil werden zwei Methoden zur Quantifizierung der Sichtbarkeit von TLAs beschrieben, eine im Zeitbereich und eine im Frequenzbereich, welche zur Quantifizierung der Wahrnehmbarkeit von TLAs genutzt werden können. Drei verschiedene Umsetzungen dieser Methoden in spezifische Sichtbarkeitsmessungen werden als Beispiel angeführt. Im folgenden Teil werden praktische Leitlinien für die Prüfung von Lichtquellen

skizziert. Abschließend werden Empfehlungen für die Verwendung der Definitionen und Quantifizierungsmethoden sowie Hinweise für künftige Arbeiten gegeben.

1 Introduction

1.1 Background

Solid-state lighting has revolutionized the world of lighting and lighting applications. The introduction of small, bright light sources which can change their luminous output at a very high rate, and which have an almost arbitrary spectral power distribution, has a profound influence on lighting quality (Schubert and Kim, 2005; Schubert et al., 2006). While in traditional lighting the search for optimal light was limited to the capabilities of the technology, the almost limitless capabilities of solid-state lighting call for a more fundamental approach, starting from human perception, and not from hardware limitations.

Some of the technological advantages can introduce perceptible side effects that were either absent or less prominent in traditional lighting systems. One such advantage is the fast reaction of solid-state light sources to the driving current. The response time can be as short as a couple of nanoseconds and results in an almost instantaneous translation of the driving current to the luminous output. As the driving current of most electric light sources is modulated, so is the light output, and such light modulation (or fluctuation in luminous quantity) with respect to time is called temporal light modulation, TLM (CIE, 2021). The simplest and most common source of TLM is unintended and results from the supply of the lighting equipment with mains power, typically modulated at 50 Hz or 60 Hz, or twice these frequencies depending on the country/region. Further, TLM can originate from interactions between the driver and dimmer electronics or as a result of disturbances in the mains power induced by other loads connected to the network.

The fast reaction time of solid-state light sources is in sharp contrast to the reaction times of some of the previous generations of electric light sources, namely the incandescent and halogen sources. These sources have emissions based on thermal process that are slower than electrical processes, which is evident in the so-called “afterglow” effect of an incandescent lamp being switched off. Metal halide lamps, like other high-intensity discharge lamps are high-output, low-resistance devices which require ballasts to control voltage and current, which in turn control the amount of modulation in the luminous output.

Temporal light modulation can also be intended for control of intensity and colour and is often used for this purpose. Using TLM ensures that the solid-state light sources are always driven in a similar operating range and results in simpler, usually linear, models of their behaviour (Pousset et al., 2010). Examples of such driving schemes are pulse-width, pulse-frequency, and pulse-density modulation, often used in colour-tuneable light sources. Figure 1 depicts three examples of time-modulated light signals, expressed as luminance, normalized to its average, with the unit one; two examples from unintended modulation arising from AC mains and one from intended modulation produced by a system that uses a pulse-width modulation scheme.

Both intended and unintended TLM sources can give rise to distortions (i.e. changes) in the perception of the environment. While in some very specific entertainment or clinical applications a distorted perception due to light modulation is desired, such as its use for potential treatment and prevention of Alzheimer's disease (Jones et al., 2019), for most everyday applications and activities, the change is detrimental and undesirable. These unwanted changes in the perception of the environment are called “temporal light artefacts” and can dramatically change the visual environment as compared to natural light and previous generations of light sources. Moreover, exposure to the TLM can lead to a decrease in visual performance, an increase in fatigue, as well as acute health problems such as epileptic seizures and migraine episodes (Wilkins et al., 2010). Understanding how TLM influences perception and what is the influence of the technological parameters (e.g. driver topology, dimming scheme) on TLM is therefore very important in the application of solid-state lighting.

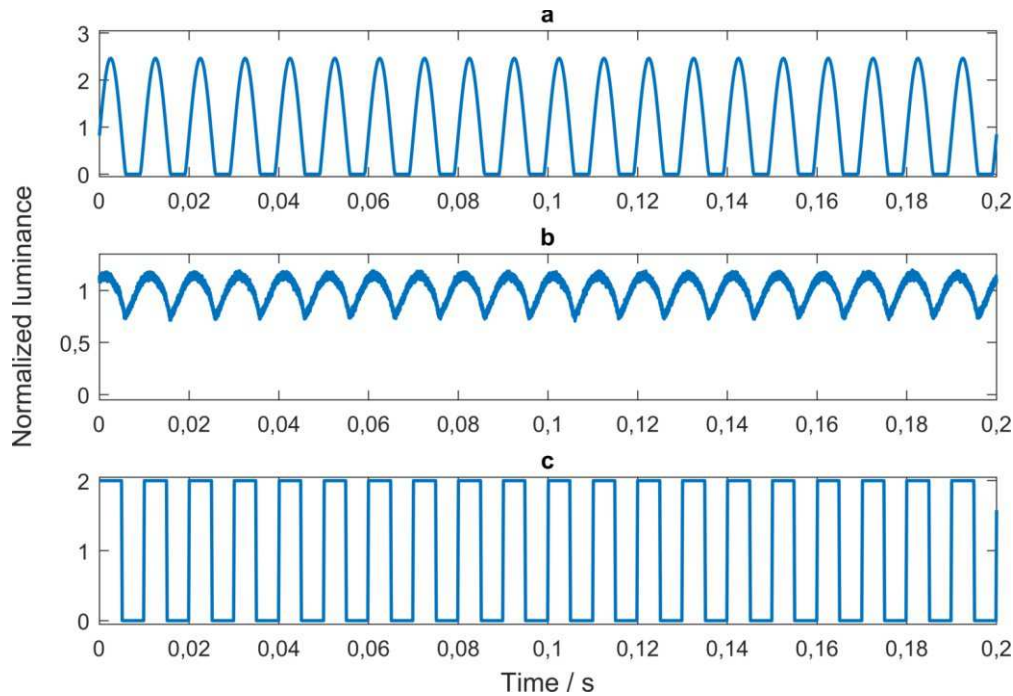


Figure 1 – Three examples of a temporal light modulation
a, b: Unintended modulation over time caused by AC mains
c: Intended modulation over time for a pulse-width-modulated system caused by the LED driver

The need for understanding the perception of temporal light artefacts is increased by the fact that limiting the TLM of light sources introduces compromises to the cost, features, or lifetime of the source, for both intended and unintended modulation. In the case of intentional modulation, lowering the visibility of temporal light artefacts can often be achieved by increasing the driving frequency of the system, which can lead to higher material costs, a decrease in efficiency (Mulligan et al., 2007) and a decrease of the capabilities of the system. Examples of such decreases of capabilities are the loss of the possibility for dimming below a given level or observing visible steps between the intensity levels (Sekulovski et al., 2011). A driving frequency within a given range can also introduce other problems like audible noise (Garcia et al., 2011). To limit the influence of the unintentional sources of modulation on the luminous output, additional measures must be implemented. These additional measures may result in increased material cost, increased size, lower efficiency, and lower lifetime of the light sources (Arias et al., 2012). As the main cause of this type of modulation is the lack of power in parts of the AC cycle, the usual remedy is to provide power storage in the form of electrolytic capacitors. However, electrolytic capacitors have the highest failure rate of all the LED drivers' components, and thus they are the main cause of the lifetime decrease of LED sources (Li et al., 2015). Additionally, their relatively large size significantly limits the design freedom, especially in small form-factor sources. Therefore, the recent research efforts have been focused on removing the electrolytic capacitors from driving solutions. Such drivers use additional filtering circuits (e.g. Miranda et al., 2020), but they can, among other things, reduce the efficiency of the light sources. For a detailed overview of capacitorless solutions see (Castro et al., 2019). All the above-mentioned issues are aggravated in the presence of legacy dimmers (Rand et al., 2007). Thus, the design of LED-driving electronics entails trade-off between lowering the visibility of temporal light artefacts, while maintaining the efficiency of the produced light, and controlling the features, lifetime, cost, and size of the light sources (Arias et al., 2012; Castro et al., 2019).

The potential negative effect of temporal light artefacts has prompted lighting manufacturers, lighting application specialists, universities, standardization bodies (IEEE, 2015), and governments to look for ways to quantify the effect and to come to a better understanding of the temporal quality aspects of lighting systems (Poplawski and Miller, 2013). For this reason,

CIE established TC 1-83 “Visual Aspects of Time-Modulated Lighting Systems” to address this issue. This document is the result of the activities performed in TC 1-83, and it provides an overview of the current understanding of the methods to predict the visibility of temporal light artefacts.

1.2 Scope

The scope of this document covers the visible effects of time-modulated lighting systems, based on white-light sources. Almost all effects that can be directly perceived by a human observer in an environment that includes time-modulated light sources are in the scope of this document. This includes both direct observation of the temporal light modulation (flicker and flashes) and interactions with the movement of the observer or objects within the lit environment.

Furthermore, the visibility of time-modulated light effects depends on many environmental factors that differ for each application. For those parts of the document which are specific to an application or a set of applications, the applicability is clearly stated.

The following effects are not in the scope of this document:

- 1) Modulation schemes that change the spectrum of the light as a function of time, while maintaining the same luminous intensity, can also give rise to flicker, called “chromatic flicker” or “colour flicker”. However, the chromatic channels of human vision show much lower temporal sensitivity compared to the achromatic channel (Swanson et al., 1987; Perz, 2010). For most lighting systems, achromatic flicker is the dominant and more critical effect. Predictive models based on the response of the visual system to achromatic flicker, measured in psychophysical experiments, are suitable because it appears to closely correlate with responses of relevant retinal ganglion and lateral geniculate nucleus cells (Purpura et al., 1990; Lee et al., 1989). Conversely, studies suggest that neuronal responses to chromatic flicker are perceptually inaccessible at least up to the primary visual cortex (Lee et al., 1989; Gur and Snodderly, 1997). For this reason, no models that describe the visibility of chromatic flicker will be presented in this document.
- 2) This document does not cover so-called flashing light, which consists of TLM at very low frequencies such as 1 Hz and used for beacons and traffic warning lights for increased visibility or conspicuity.
- 3) Time-modulated lighting systems might also give rise to non-visual effects among the user population, including some health-related issues (IEEE, 2015). These effects are important, but substantial work is still needed to understand the link between light modulation and the non-visual effects (CIE, 2017) and therefore the non-visual effects are outside the scope of this document.
- 4) The amount of modulation that is acceptable (beyond the visibility thresholds) can be dependent on the specific application. Acceptable limits to TLM might be more precisely defined by other effects and factors that are not part of this document. Acceptability thresholds are therefore not within the scope of this document.
- 5) The scope does not include temporal sensitivity of persons diagnosed with a syndrome or disease that may lead to visual pathophysiology, such as Autism Spectrum Disorder, Developmental Dyslexia, Parkinson’s disease or Multiple Sclerosis (e.g. Tobimatsu and Celesia, 2006; Brown et al., 2020). The sensitivity of such observers is important; however, different syndromes/diseases are linked to different temporal processing deficiencies and thus each of these observer groups require separate research lines.
- 6) The scope includes conditions where a human observer directly interacts with an environment lit by a time-modulated light source. Thus, unwanted artefacts through interactions with capture and reproduction systems such as television (TV) recording, broadcasting and personal video are outside the scope of this work. Interactions with non-human vision, like animal, insect or machine vision are also outside the scope.

- 7) This document covers the visible effects of electric light sources. As such, the temporal effects produced by light coming from the Sun (e.g. reflections off the water) are outside of the scope.

1.3 Structure of the document

Temporal light modulation (TLM) can give rise to various perceptual effects, called temporal light artefacts (TLAs). In Clause 2 definitions for terms describing fundamental concepts characterizing the TLM stimulus are given, explained by means of two examples. Then, a set of definitions for terms related to TLAs is given.

The topic of the visibility of temporal light modulation is not a new one and especially there is an abundance of scientific literature on the flicker visibility that dates back to the 1960s. In what follows, Clause 3 of this document gives a concise overview of relevant literature on the topic.

Depending on the type of modulation that is predominantly present, specific methodologies for analysis are appropriate. On the one hand, periodic modulations that are presented long enough to be perceived, having a well-defined set of frequencies for which phase information can be omitted, are better suited for frequency-domain analysis. On the other hand, aperiodic modulations, periodic modulations with frequencies for which phase information cannot be omitted, transient modulations or modulations with random frequency components are better suited for time-domain analysis. Clause 4 discusses both methodologies and gives two general frameworks, in which the effects of both types of modulations can be quantified. Examples of implementations of the framework are included.

Clause 5 briefly describes practical guidelines on testing light sources. Finally, Clause 6 formulates recommendations for the methods to be used to predict the visibility of temporal light artefacts. Furthermore, recommendations for future work are given as there is a clear need for validation and extension of the knowledge on the visibility of TLAs.

2 Terms, definitions and fundamentals

2.1 Introduction

Temporal light modulation, which is a stimulus (see also TN 012:2021, 2.1 (CIE, 2021)), can give rise to several different temporal light artefacts, which are perceived qualities of light. As such, a set of definitions for terms describing fundamental concepts characterizing the TLM stimulus is given in 2.2, and definitions related to visibility aspects (i.e. visual response) of TLM, in 2.3. This stimulus-response distinction has been represented in the definitions published in CIE TN 006:2016 (CIE, 2016), and in the case of the term “flicker” also in the definition published in CIE S 017:2020 (CIE, 2020). However, it should be noted that the definitions in 2.2 are introduced in this document; physical characteristics of TLM are explained but not defined in TN 006. Additionally, the newly defined concepts are explained by means of two practical examples. The terms given in 2.3 correspond to the terms in TN 006, however some of the definitions have been modified. Notably, notes have been added to the definitions of “flicker”, “stroboscopic effect” and “phantom array effect”, giving the minimal requirements for detection, as well as other visibility conditions. The minimal requirements for the detection are implied in the definitions of the terms first defined in TN 006; in this document they are made explicit for clarity.

2.2 Physical characteristics of temporally modulated lighting systems

2.2.1 General

In this subclause, a set of definitions for terms used for physical characterization of temporally modulated lighting systems is given. The defined terms are further explained by means of examples of a periodic temporal waveform and a simple spatial layout.

2.2.2 Terms and definitions

2.2.2.1

temporal waveform, <of a luminous quantity>

manifestation or representation of variation in a luminous quantity emitted by a light source as a function of time

Note 1 to entry: The representation can be given by e.g. a graph, a plot, equations, a table of coordinates, or statistical data.

Note 2 to entry: In most practical applications, temporal waveforms are represented by their digitized version, with a discretized representation of both time and luminous output. Non-periodic waveforms cannot be represented with a finite time sample and are typically approximated by a limited time digitized version.

Note 3 to entry (only valid for this document): In this document, for brevity, the term "waveform" is used meaning "temporal waveform".

2.2.2.2

periodic temporal waveform

temporal waveform identically recurring at equal intervals of the time

Note 1 to entry: The function $f(t)$ is periodic when $f(t + T) = f(t)$ for some positive T .

Note 2 to entry: Common periodic waveforms include rectangular pulse train (IEC 60050-103:2009, Entry 103-05-21), and sinusoidal waveform (IEC 60050-103:2009, Entry 702-03-09).

Note 3 to entry: The definition is based on the definition of the adjective "periodic" in IEC 60050-103:2009 (Entry 103-05-09).

2.2.2.3

period

smallest positive difference T between two values of the independent variable t of a function $f(t)$ at which the function's values are identical for any value of t : $f(t + T) = f(t)$

Note 1 to entry: If $f(t)$ describes the variation of a quantity with time, the period is sometimes called "period duration" in English.

[SOURCE: IEC 60050-103:2009, Entry 103-06-01]

2.2.2.4

frequency

reciprocal of the period

Note 1 to entry: The symbol f is mainly used when the period is a time. The symbol ν (nu) is mainly used in optics.

Note 2 to entry: The coherent SI unit of frequency is the hertz, Hz.

[SOURCE: IEC 60050-103:2009, Entry 103-06-02]

2.2.2.5**duty cycle***D*

ratio of the active period, t_a , to the period, t , of a periodic temporal waveform

Note 1 to entry: The active period, t_a , is the time for which the intensity is above 10 % from the maximum intensity of the waveform. The active period is sometimes called “high state” or “ON state”.

Note 2 to entry: The duty cycle can vary from 0 to 1. At a duty cycle of 1 the luminous intensity emitted by a source is constant with respect to time.

Note 3 to entry: The duty cycle is usually used to describe a rectangular pulse train (see IEC 60050-702:1992, Entry 702-03-10 (“rectangular pulse”) and Entry 702-03-11 (“pulse train”)). A rectangular pulse train, together with the special case of a square waveform, are commonly measured in various lighting applications, but the application of duty cycle is not limited to only such waveforms. Though it is rare, duty cycle can also be applied to a triangular or sawtooth waveform.

Note 4 to entry: The definition is based on the definition of “pulse duty factor” in IEC 60050-702:2009 (Entry 102-03-09), and on the definition of “duty factor” in IEEE Std 181-2011 (IEEE, 2011).

2.2.2.6**modulation depth****amplitude of fluctuation of the luminous flux** D_M^1

relative amplitude of the periodic fluctuation of the luminous flux as calculated by the ratio of the difference between the maximum and the minimum instantaneous luminous flux, $\Phi_{\max}$ and $\Phi_{\min}$ respectively, to the sum of both of these values:

$$\frac{\Phi_{\max} - \Phi_{\min}}{\Phi_{\max} + \Phi_{\min}}$$

Note 1 to entry: For temporal waveforms for which the time average, $\bar{\Phi}$, is equal to $(\Phi_{\max} + \Phi_{\min}) / 2$, the modulation depth is equal to: $D_M = (\Phi_{\max} - \Phi_{\min}) / (2 \bar{\Phi})$.

Note 2 to entry: The modulation depth can be applied also for “luminance” and “illuminance”. Additional photometric quantities can be used.

Note 3 to entry: The modulation depth has unit one and is usually expressed in per cent (%).

[SOURCE: CIE S 017:2020, Entry 17-27-115 – modified: Synonym “modulation depth” added as preferred term and symbol added; in Notes 1 and 2 “amplitude of fluctuation” replaced with “modulation depth”; Notes 1 and 2 moved to Notes 2 and 3, respectively; new Note 1 added; Note 4 omitted]

2.2.2.7**luminance contrast, <of a TLM stimulus>** C_M

quantity relating to the difference in luminance between the TLM stimulus and the background

¹ Note that the abbreviation of the term “modulation depth”, MD, is often used as quantity symbol, too. This does not conform with the CIE rules and the rules of other standardizing organizations regarding the presentation of quantity symbols. For that reason, the symbol D_M is introduced for the quantity “modulation depth” in this document.