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A stochastic process based reliability prediction method for LED driver

Bo Sun[a], Xuejun Fan[b,*], Willem van Driel[c,d], Chengqiang Cui[a,*], Guoqi Zhang[d]

[a] Guangdong University of Technology, Guangzhou, China
[b] Lamar University, Beaumont, TX, USA
[c] Phillips, Eindhoven, the Netherlands
[d] Delft University of Technology, Delft, the Netherlands

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ABSTRACT

In this study, we present a general methodology that combines the reliability theory with physics of failure for reliability prediction of an LED driver. More specifically, an integrated LED lamp, which includes an LED light source with statistical distribution of luminous flux, and a driver with a few critical components, is considered. The Wiener process is introduced to describe the randomness of lumen depreciation. The driver's survival probability is described using a general Markov Chain method. The system compact thermal model (physics of failure model) is developed to couple with the reliability methods used. Two scenarios are studied: Scenario S1 considers constant driver's operation temperature, while Scenario S2 considers driver's temperature rise due to lumen depreciation. It has been found that the wide life distribution of LEDs will lead to a large range of the driver's survival probability. The proposed analysis provides a general approach for an electronic system to integrate the reliability method with physics models.

1. Introduction

In recent years, physics-of-failure (PoF) models have been integrated with statistics theories for reliability assessment of systems [1,2]. For example, PoF-based degradation models have been used for modeling common-cause failures [3]. The sensitivity analysis has been integrated with SPICE simulation for tolerance design of circuits [4]. PoF models have been utilized for the life cycle prediction of solder joints [5]. A multi-state physics model has been developed for degradation of components of a system [6]. The physics-based modeling combined with uncertainties propagation has been used as virtual tests to create data [7]. Several PoF models have been integrated with Monte Carlo simulation and Weibull analysis for component reliability analysis [8]. Probabilistic-physics-of-failure (PPoF) based reliability assessment methods have been proposed [9]. A probabilistic PoF-based framework has been used with uncertainty quantification method for life prediction of turbine discs [10].

Light emitting diode (LED) lamps have become the leading candidate for future lighting in recent years due to advantages such its superior energy efficiency, environmental friendliness, and long lifetime [11–14]. An LED lamp mainly comprises an LED light source, a driver, control gear, secondary optical parts, and heat dissipation components [11,12]. Although LED's lifetime is up to 25,000 to 100,000 h, LED lamps may have a much shorter lifetime due to LED driver [15]. The driver is considered as one of the major reliability bottlenecks of LED lamps [16]. It has been found that an elevated operating temperature can accelerate the degradation of drivers [17] and lead to the catastrophic failure [18], which limits the lifetime of the entire lamp.

The randomness of the LED's lumen depreciation has been well studied for LED itself. For instance, a Gamma process based approach has been used to predict LED's degradation in accelerated conditions [19]. The Gamma process together with copula function has been applied for reliability modeling of LED light system [20]. The nonlinear filter [21] and particle filter [22] have been used for life test for white LEDs. Owing to its capability of minimizing the mean squared estimation error [23] and well-developed implementations [24–28], Wiener process has been utilized for lumen depreciation and color shift [15,29]. A generalized Wiener process degradation model with two transformed time scales has been proposed [30]. An adaptive Wiener process model has been utilized to predict remaining useful life of LEDs [26]. However, few of these models consider the impact of lumen decay on driver's reliability.

This study presents a general methodology that combines the reliability theory with physics of failure for reliability prediction. More specifically, an integrated LED lamp, which includes an LED light source with statistical distribution of luminous flux, and a driver with a few critical components, is considered. The Wiener process is introduced to describe the randomness of lumen depreciation. The

* Corresponding author.
E-mail addresses: xuejun.fan@lamar.edu (X. Fan), cqcui01@qq.com (C. Cui).

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Notations

t	Aging duration
$\Phi(t)$	Lumen maintenance at time t
β	Depreciation rate of the LED light source
$W(t)$	Stochastic distribution of the lumen depreciation
α	Increasing rate of the standard deviation
$p[\Phi(t)]$	Probability density for $\Phi(t)$
P_{LED}	Total power of the LED light source
P_{Opt}	Optical power of the LED light source
$R_D(t)$	Driver's survival probability at time t
$h_D(t)$	Hazard rate of the driver's failures
h_{Di}	Hazard rate of the power diode
h_{IC}	Hazard rate of the control IC
$T_{j,\ Di}$	Junction temperature of power diode
$T_{j,\ IC}$	Junction temperature of control IC
λ_{Di}	Basic hazard rate of power diode
λ_{IC}	Basic hazard rate of control IC
$E_{a,\ Di}$	Activation energy of power diode
$E_{a,\ IC}$	Activation energy of the control IC
κ	Boltzmann constant
T_A	Ambient temperature
$T_{A,\ in}$	Air temperature inside the lamp
$T_{C,\ Di}$	Case temperatures of the power diode
$T_{C,\ IC}$	Case temperatures of the control IC
R_{th1}	Thermal resistance between air surrounding driver and lamp's case
R_{th2}	Thermal resistance between lamp's case and ambient
$R_{th1,\ Di}$	Convective thermal resistance of power diode
$R_{th1,\ IC}$	Convective thermal resistance of control IC
$R_{th2,\ Di}$	Conductive thermal resistance of power diode
$R_{th2,\ IC}$	Conductive thermal resistance of control IC
$P_{th,\ LED}$	Thermal power of the LED light source
$P_{th,\ Di}$	Thermal power of power diode
$P_{th,\ IC}$	Thermal power of control IC

driver's survival probability is described using a general Markov Chain method. As a physics of failure model, a system-level compact thermal model of the LED lamp is developed to couple with the reliability methods used.

This paper is organized as follows. Section 2 describes the lumen depreciation model of the LED light source using the Wiener process. Section 3 explains the reliability model of selected LED driver. Section 4 introduces the compact thermal model of the LED lamp. Section 5 defines various scenarios of case studies and discusses the results. Section 6 concludes this work.

2. Lumen depreciation model

The exponential model has been considered as the most adopted lumen depreciation model in literature [11,12,14], owing to its capability in describing the accelerated test results. In the present study, the Wiener process is introduced to describe randomness of the lumen depreciation [15]. Therefore, the exponential Wiener process for lumen maintenance is used. Other Wiener processes or stochastic processes may also be used. The lumen maintenance at time t, the ratio of luminous flux remaining at time t to its initial value, can be described by the following function:

$$\Phi(t) = e^{-\beta t} + W(t) \tag{1}$$

where, $\Phi(t)$ is the lumen maintenance at time t, β is the depreciation rate, $W(t)$ is the stochastic disturbance of the lumen depreciation at time t, which follows the normal distribution [23]:

$$W(t){:}\ N(0, \alpha t) \tag{2}$$

Hence, at any given time t, the lumen maintenance also follows the normal distribution:

$$\Phi(t){:}\ N(e^{-\beta t}, \alpha t) \tag{3}$$

In this model, the mean values of lumen maintenance degrade exponentially, and the standard deviations increase linearly at a rate of α. Considering the normal distribution of the lumen maintenance, this work defines $\pm\ 3\alpha t$ as the lower and upper bound. The boundary condition is $\Phi(0) = 1$. Moreover, the probability density function at time t can be obtained by the following equation [23]:

$$p[\Phi(t)] = \frac{1}{\sqrt{2\pi}\alpha t} e^{-\left[\frac{\Phi(t)-e^{-\beta t}}{\sqrt{2}\cdot\alpha t}\right]^2} \tag{4}$$

To determine the parameters in the lumen depreciation model by Eq. (3), 30 LEDs, as shown in Fig. 1, were tested at 328 K (55 °C) and the rated input current for 2000 h. Each light source has 24 LED packages in parallel. The input power and lumen maintenance of each sample was tested by an integrating sphere system.

At time $t = 0$, the rated input current of the LED light source is 120 mA, the average forward voltage is about 55.42 V, total power P_{LED}=6.65 W DC and optical power P_{Opt}=2.51 W DC. Tested lumen maintenance distributions as functions of time are shown in Fig. 2. Normality tests were carried out on the results to check the normality of the lumen maintenance distribution.

The P-value from a normality test is a statistical indicator representing the probability of the observed sample to follow the assumed distribution. A larger P value indicates that the obtained distribution follows the assumed distribution. $P = 0.05$ is the threshold value for the normality test in statistics. The obtained P-values are shown in Fig. 3. It can be seen from the results that the P values of lumen maintenance distribution are much higher than 0.05. Thus, the normal distributions in Eq. (3) are confirmed.

The mean values and standard deviations of lumen maintenance distribution are displayed in Fig. 4. The obtained test results are fitted

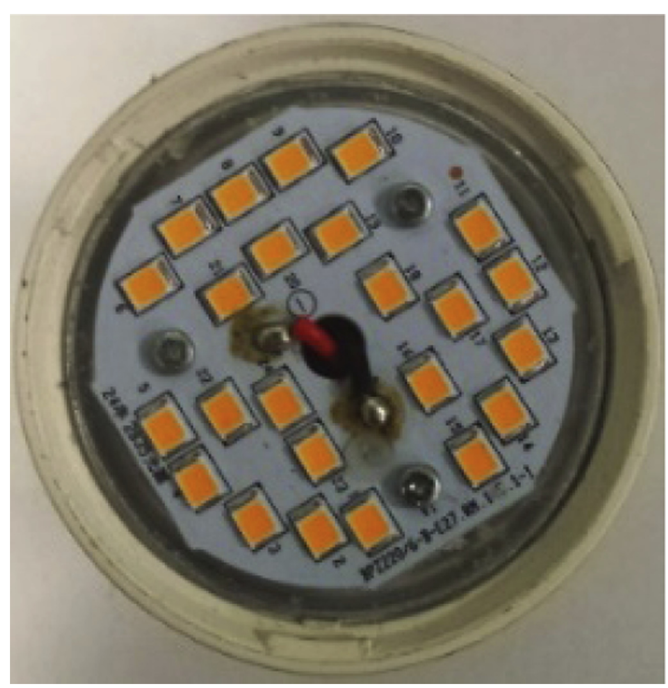

Fig. 1. LED light sources in the selected lamp.

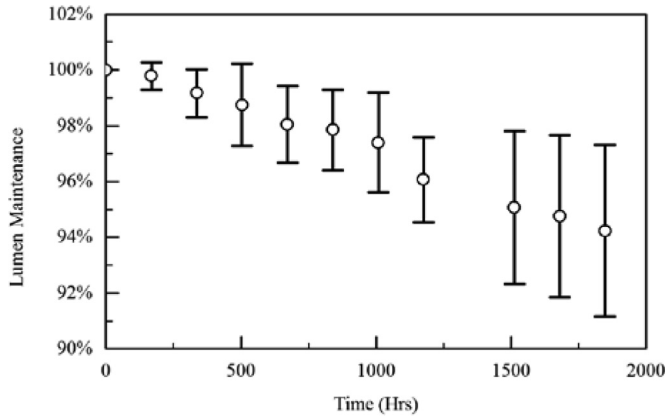

Fig. 2. Lumen maintenance distributions.

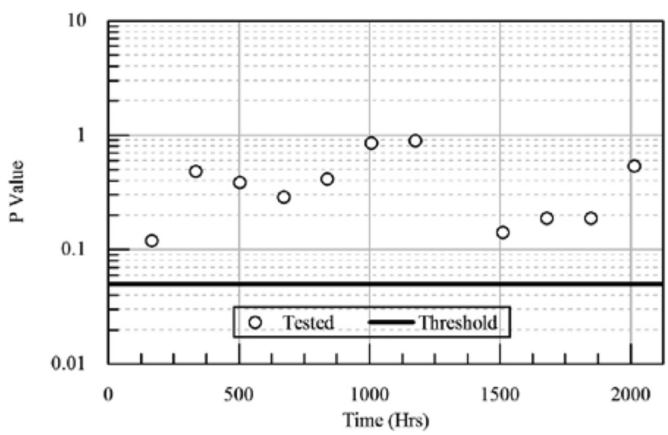

Fig. 3. Normality test results.

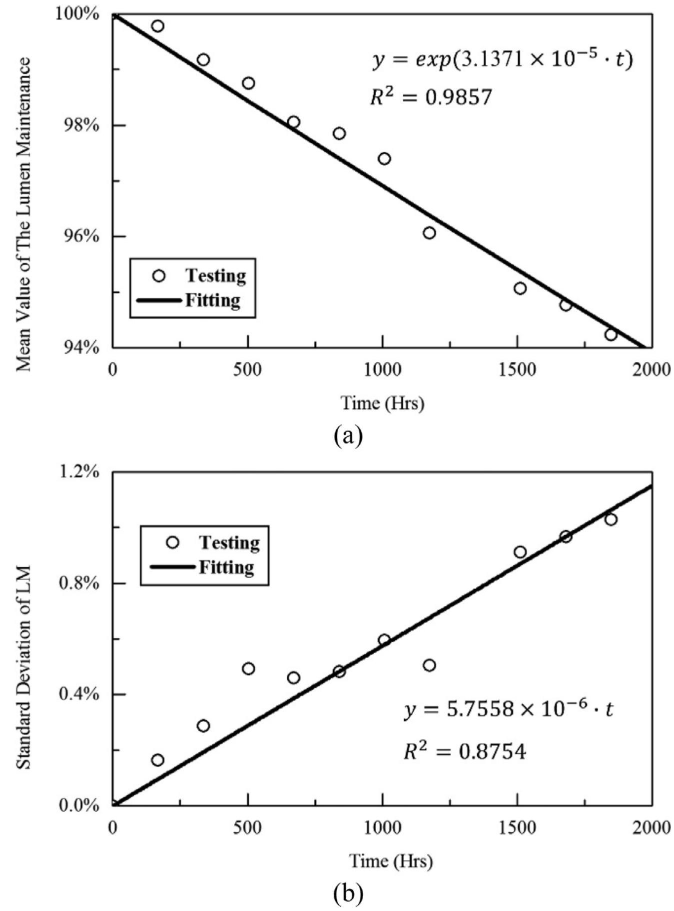

Fig. 4. (a) Mean values and (b) standard deviations of the lumen deprecation.

by functions given by Eq. (3) using the least-square method. The parameter of curve fitting α and β are 5.7558×10^{-6} and 3.1371×10^{-5} respectively. The R^2 values of the predicted mean values and standard deviations are 0.9857 and 0.8754 respectively. Hence, the test results show a good agreement with the proposed model.

3. Led driver's reliability model

For an electronic system, the catastrophic failure depends on current conditions only, not related to its operation history. Therefore, the probabilities of a system can be obtained by Markov Chain [31,32]. For a system which has N operation states, probability of the system at time $t + \Delta t$ only relates to the state at time t:

$$X(t + \Delta t) = X(t)P \tag{5}$$

where P is system's transition matrix:

$$P = \begin{bmatrix} h_{0\to0} & h_{0\to1} & \cdots & h_{0\to n-1} \\ h_{1\to0} & h_{1\to1} & \cdots & h_{1\to n-1} \\ \vdots & \vdots & \ddots & \vdots \\ h_{n-1\to0} & h_{n-1\to1} & \cdots & h_{n-1\to n-1} \end{bmatrix} \tag{6}$$

where $h_{i\to j}$ means the probability of State i transfers to State j.

Fig. 5 displays the driver circuit used in this paper. This work selects a quasi-resonance driver with two critical components: the power diode D1 and the control IC U1.

Since an overall catastrophic failure of the driver is considered, the driver has only two states: healthy (State 1) and fail (State 0). Fig. 6 gives the diagram of the LED driver.

The $P_1(t)$ and $P_0(t)$ are probabilities of State 1 and State 0 at time t. The transition matrix P degrades to:

$$P = \begin{bmatrix} h_{0\to0} & h_{0\to1} \\ h_{1\to0} & h_{1\to1} \end{bmatrix} \tag{7}$$

The overall probability of the driver stays unchanged, thus:

$$h_{0\to0} + h_{1\to0} = h_{0\to1} + h_{1\to1} = 0 \tag{8}$$

Meanwhile, the selected driver is an unrecoverable system, hence, $h_{0\to1} = h_{1\to1} = 0$. At time t, the probability of the driver transits from State 1 to State 0 ($h_{1\to0}$) is defined as the hazard rate $h_D(t)$. Finally, the occupational probabilities can be given as follows [31]:

$$\frac{d}{dt}\begin{bmatrix} P_1(t) \\ P_0(t) \end{bmatrix} = \begin{bmatrix} -h_D(t) & 0 \\ h_D(t) & 0 \end{bmatrix}\begin{bmatrix} P_1(t) \\ P_0(t) \end{bmatrix} \tag{9}$$

Since the survival probability of the driver at time t $R_D(t)$ equals to $P_1(t) - P_0(t)$. Thus:

$$\frac{dR_D(t)}{dt} = -h_D(t)\cdot R_D(t) \tag{10}$$

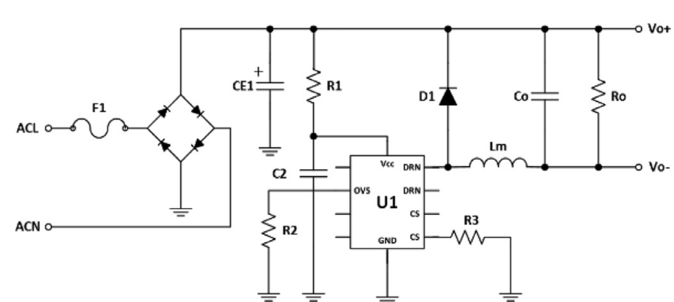

Fig. 5. Circuit of LED driver [33].

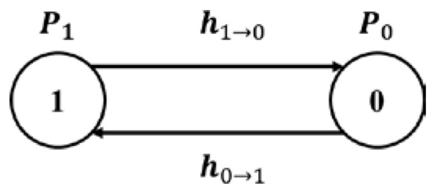

Fig. 6. Diagram of the LED driver.

As boundary conditions $P_1(0) = 1$ and $P_0(0) = 0$, the function $R_D(t)$ is reduced to the basic form

$$R_D(t) = e^{-\int_0^t h_D(x)\cdot dx} \tag{11}$$

Markov Chain provides a general tool to calculate reliability of a system [31]. For the purpose of clarity, this paper focuses on the simplified case study given by Eq. (11).

Assuming that the failure of each critical component is independent to each other, $h_D(t)$ is approximately the sum of hazard rates of critical components [31]:

$$h_D(t) = h_{Di}(t) + h_{IC}(t) \tag{12}$$

where $h_{Di}(t)$ and $h_{IC}(t)$ are hazard rates of the power diode and the control IC respectively. $h_{Di}(t)$ and $h_{IC}(t)$ can be obtained by [34]:

$$h_{Di}(t) = h_{Di}[T_{j,Di}(t)] = \lambda_{Di}\cdot e^{\frac{-E_{a,Di}}{\kappa\cdot T_{j,Di}(t)}} \tag{13}$$

$$h_{IC}(t) = h_{IC}[T_{j,IC}(t)] = \lambda_{IC}\cdot e^{\frac{-E_{a,IC}}{\kappa\cdot T_{j,IC}(t)}} \tag{14}$$

where, $T_{j,\ Di}$ and $T_{j,\ IC}$ are junction temperatures, λ_{Di} and λ_{IC} are basic hazard rates, $E_{a,\ Di}$ and $E_{a,\ IC}$ are the activation energy of the power diode and the control IC. In this work, λ_{Di}, λ_{IC}, $E_{a,\ Di}$ and $E_{a,\ IC}$ are obtained from the empirical models [34], and $T_{j,\ Di}$ and $T_{j,\ IC}$ can be calculated by the compact thermal model of the selected LED lamp. Finally, the MTTF of the driver is a function of $R_D(t)$:

$$MTTF = \int_0^\infty R_D(t)\cdot dt \tag{15}$$

4. Led lamp's compact thermal model

As a carrier for the purpose of study, a commercial LED bulb lamp, shown in Fig. 7, is selected.

A compact thermal model of the LED lamp is used to obtain the relationship between LED's thermal dissipation and junction temperatures of critical components in the driver. For the considered lamp, there are several heat sources: the LEDs and driver components. The heat dissipation from LEDs and driver will lead to an increase in the junction temperature of driver's components. Due the absence of the potting material, there is an air gap between the driver and the lamp's body.

Fig. 8 displays the compact thermal model. $T_{A,\ in}$ is the air temperature inside the lamp, T_A is the ambient temperature, $T_{C,\ Di}$ and $T_{C,\ IC}$ are the case temperatures of power diode and IC respectively, $T_{j,\ Di}$ and $T_{j,\ IC}$ are the junction temperatures of the diode and IC respectively. R_{th1} is the thermal resistance between the air surrounding the driver and the lamp's case, R_{th2} is the thermal resistance between the lamp's case and the ambient, $R_{th1,\ Di}$ and $R_{th1,\ IC}$ are convective thermal resistances, $R_{th2,\ Di}$ and $R_{th2,\ IC}$ are conductive thermal resistances. $P_{th,\ LED}$ is the thermal power of the LED light source, $P_{th,\ Di}$ and $P_{th,\ IC}$ are thermal power of the diode and the IC respectively. The heat from other components of the driver is considered in the total thermal power of the driver.

Once the lamp reaches thermal equilibrium point, for any critical component i, the case temperature $T_{C,\ i}$ and junction temperature $T_{j,\ i}$ are functions of the component's thermal power $P_{th,\ i}$:

$$T_{C,i} = P_{th,i}\cdot(R_{th1,i} + R_{th2,i}) + T_{A,in} \tag{16}$$

In this work, $R_{th1,\ Di}$ and $R_{th1,\ IC}$ are obtained experimentally, and $R_{th2,\ Di}$ and $R_{th2,\ IC}$ are obtained from data-sheets [33,35]. The air temperature inside the lamp $T_{A,\ in}$ is a function of total thermal power of the lamp:

$$T_{A,in} = (R_{th1} + R_{th2})\cdot(P_{th,LED} + P_{th,D}) + T_A \tag{17}$$

where, $P_{th,\ D}$ is total thermal power of the driver. As thermal resistances of the lamp, $R_{th1} + R_{th2}$ can be measured experimentally. Base on the energy conservation law, the $P_{th,\ LED}$ under influence of the lumen depreciation can be obtained by:

$$P_{th,LED} = P_{LED} - P_{Opt}\cdot\Phi(t) \tag{18}$$

where, P_{LED} is the input power and P_{Opt} is the initial optical power of the LED light source. As a result, the stochastic process model is integrated with physics-based models.

The electrical-optical tests were carried out on the driver to measure its power consumption. The driver was tested in room temperature (298 K). The root mean square values of operation voltages and current of the IC and the power diode were measured by a power meter. Meanwhile, the total thermal power of the driver was measured as well. Table 1 lists the electronic test results.

The thermal tests were carried out to measure the thermal resistances $R_{th1} + R_{th2}$ and validate the compact thermal models and. Firstly, the lamp was placed at room temperature (298 K) and natural convection, and the air temperature inside the lamp was measured by thermocouples. Thermocouples were placed inside the air gap, without contact with the lamp body or the driver. The light source and the driver were driven by programmable power supplies respectively. The output wires of the driver were connected to an electronic load outside of the lamp. A 2 m integrating sphere system was used to measure optical power of the lamp. As the difference between total input power and optical power, the total thermal power of the lamp, $P_{th,LED} + P_{th,D}$, can be obtained. By adjusting the input power, the thermal resistance $R_{th1} + R_{th2}$ can be calculated using Eq. (17).

The temperature difference between the air surrounding the driver and the ambient as a function of the lamp's total thermal power $P_{th,LED} + P_{th,D}$ is shown in Fig. 9. The air temperature inside the lamp increases linearly with the total thermal power. Fitted by Eq. (17) via the least-square method, the thermal resistance $R_{th1} + R_{th2}$ is about 8.62 K/W. The R^2 values of the air temperature is 0.9960. The proposed thermal model also shows a good agreement with test results.

The driver was also tested at room temperature (298 K) and convection-free condition to obtain the condition as inside the LED lamp. Case temperatures of the IC and the power diode are measured by an IR camera. As shown in Fig. 10, the temperature differences between the cases of IC and power diode, and IC and ambient are 14.52 K and 15.79 K respectively. Fitted by Eq. (16), $R_{th1,\ IC} = 200$ K/W and $R_{th1,\ Di} = 120$ K/W.

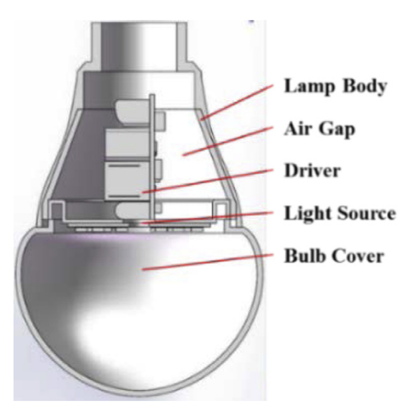

Fig. 7. The schematic of LED lamp.

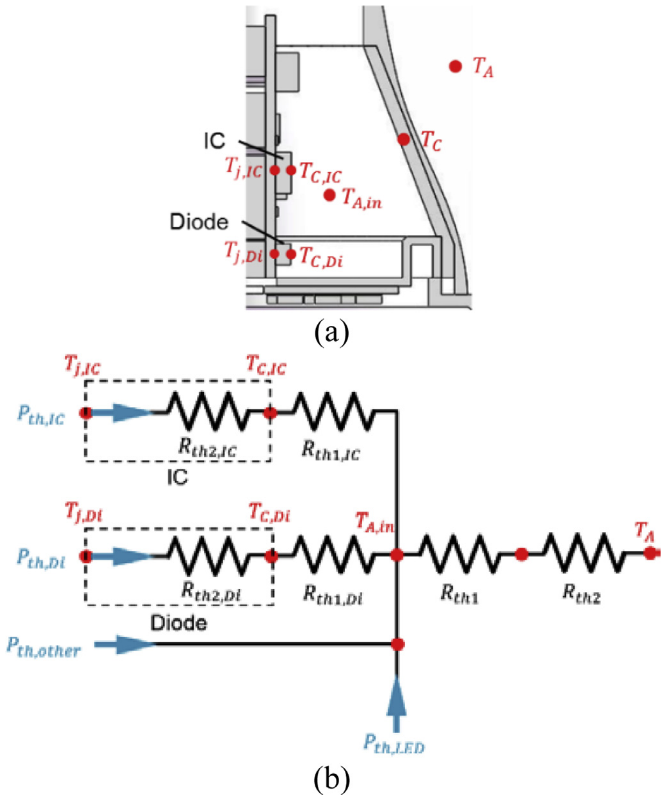

Fig. 8. (a) The selected lamp structure with (b) the compact thermal model.

Table 1
Electronic test results.

	Voltage	Current	Power
IC	0.756 V	0.095 A	$P_{th,\ IC}$ = 0.072 W
Diode	1.109 V	0.121 A	$P_{th,\ Di}$ = 0.133 W
LEDs	55.42 V	0.120 A	P_{LED} = 6.650 W
Total	–	–	$P_{th,\ D}$ = 0.640 W

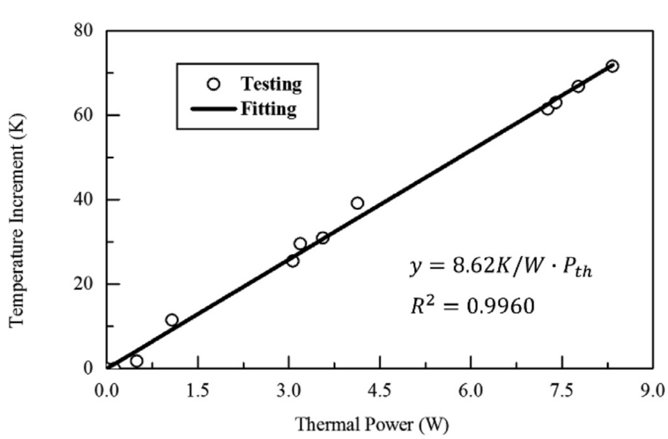

Fig. 9. Air temperature curve inside the lamp.

5. Case studies and results

5.1. Definition of scenarios

The proposed approach provides a general methodology for an electronic system with distinct failure modes such as degradation and catastrophic failure combined. As a case study, as listed in Table 2, two different scenarios are considered in this work. In Scenario S2, the driver's catastrophic failure and LED's lumen depreciation are both considered; whereas in Scenario S1, only the driver's catastrophic failure is taken into consideration as a comparison. Table 3 summarizes the simulation parameters used, which are obtained from the empirical models [34], tests in Section 4 and datasheets of critical components [33,35], respectively.

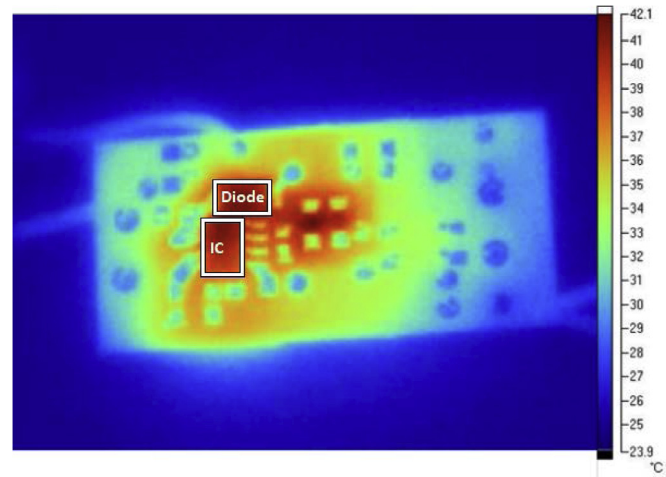

Fig. 10. Case temperature of the driver.

5.2. Results and discussions

The temperature difference between the air surrounding the driver and the ambient in Scenario S2 obtained by Eq. (17) is shown in Fig. 11. During lumen depreciation process, the mean value of the air temperature surrounding the driver increases about 10 K in 20,000 h. In the same time period, the upper bound and lower bound rise about 3 K and 18 K respectively. The randomness of the lumen depreciation exhibits an important effect on driver's operation condition.

By considering the aforementioned ever-increasing temperature, $h_D(t)$ can be obtained from Eqs. (12)–(14). As shown in Fig. 12, the mean value of the hazard rate increases from 5.5691×10^{-5} to 1.0800×10^{-4}. Further, the upper bound and lower bound have changed to 1.7241×10^{-4} and 6.6347×10^{-5} respectively, after 20,000 h aging.

The survival probability of the driver can be obtained from Eq. (11). The survival probability curve of the driver for each scenario is displayed in Fig. 13. For Scenario S1, the driver's survival probability degrades to about 32.8% at 20,000 h. For Scenario S2, the mean value, upper bound and lower bound of the driver's survival probability drop to about 19.4%, 28.3%, and 11.6% respectively in the same period.

Table 4 lists the MTTF of the driver calculated by Eq. (15). The MTTF of Scenario S1 is about 16,000 h. The mean value, upper bound and lower bound of MTTFs of Scenario S2 are 12,600, 14,840 and 10,900 h respectively. Compared to the mean value of Scenario S2, MTTFs of Scenario S1 is about 26.9% longer, suggesting that the constant temperature assumption may bring significant errors to reliability prediction.

Compared to Scenario S1, Scenario S2 has shown wide distributions

Table 2
Scenario design.

Scenario	Condition
S1	$T_{A,in}(t) = T_{A,in}(0)$= 339K
S2	$T_{A,\ in}(t)$ rises with the lumen depreciation: Mean: $\Phi(t) = e^{-\beta \cdot t}$ Min: $\Phi(t) = e^{-\beta \cdot t} + 3\alpha t$ Max: $\Phi(t) = e^{-\beta \cdot t} - 3\alpha t$

Table 3
Simulation parameters.

Parameter	Value	Parameter	Value
α	5.7558×10^{-6}	β	3.1371×10^{-5}
P_{Opt}	2.560 W	P_{LED}	6.650 W
$P_{th,\ IC}$	0.072 W	$P_{th,\ Di}$	0.133 W
$P_{th,\ D}$	0.640 W	$R_{th1}+R_{th2}$	8.62 K/W
$R_{th1,\ IC}$	200 K/W	$R_{th1,\ Di}$	120 K/W
$R_{th2,\ IC}$	50 K/W	$R_{th2,\ Di}$	34 K/W
$E_{a,\ IC}$	0.70 eV	$E_{a,\ Di}$	0.23 eV
λ_{IC}	0.48	λ_{Di}	0.0038
T_A	298 K (25 °C)		

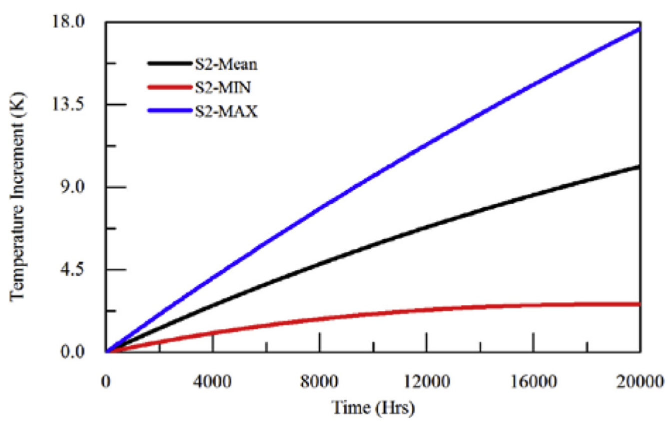

Fig. 11. Temperature differences between air surrounding the driver and the ambient.

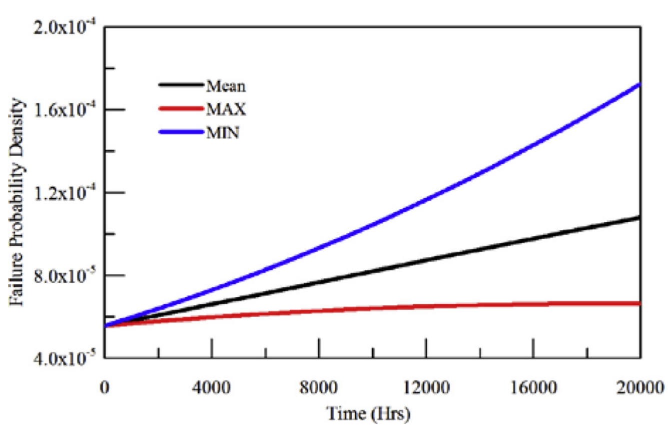

Fig. 12. Hazard rate curves of the driver.

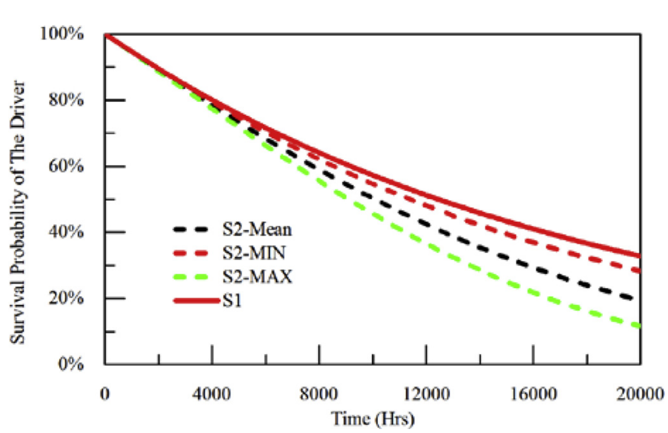

Fig. 13. Reliability curves of the driver.

Table 4
Mean time to failure of the driver.

Scenario	MTTF (h)
S1	16,000
S2-Mean	12,600
S2-Min	10,900
S2-Max	14,840

in both survival probability and MTTF. For a more realistic lifetime prediction of LED lamp, LEDs life data should be considered. The proposed analysis provides a general approach for an electronic system to integrate the reliability method with physics models.

6. Conclusions

This study presents a general methodology that combines the reliability theory with physics of failure for reliability prediction. More specifically, an integrated LED lamp, which includes an LED light source with statistical distribution of luminous flux, and a driver with two critical components, is considered. The Wiener process is introduced to describe the randomness of lumen depreciation. The driver's survival probability is described using a general Markov Chain method. A compact thermal model is developed to couple with the reliability methods used. Two scenarios are studied: Scenario S1 considers constant driver's operation temperature, while Scenario S2 considers driver's temperature rise due to lumen depreciation.

For Scenario S1, the constant driver's temperature is assumed. After 20,000 h aging, the survival probability of the driver degrades to about 32.8%. The driver's MTTFs is about 17,300 h. For Scenario S2, the thermal model is introduced, therefore, the mean value, upper bound and lower bound of air temperature surrounding the driver can be obtained. As a result, the mean value, upper bound and lower bound of the driver's survival probability decrease to about 19.4%, 28.3%, and 11.6% respectively after 20,000 h. It is found that the wide life distribution of LEDs can lead to a large variation of the driver's survival probability.

The proposed analysis provides a general approach for an electronic system to integrate the reliability method with physics models. In addition to the exponential Wiener process, the proposed approach can also consider other Wiener processes or stochastic processes to describe the degradation. The Markov Chain provides a general method to calculate reliability of an electronic circuit according to operation conditions. As for the physics-based model, the physics other than thermal theory, such as fatigue, creep, or diffusion based model, can be combined in the proposed approach for many applications in an electronic system.

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