EKSPLOATACJA I NIEZAWODNOŚĆ
MAINTENANCE AND RELIABILITY

Eksploatacja i Niezawodnosc – Maintenance and Reliability

Volume 24 (2022), Issue 2

journal homepage: http://www.ein.org.pl

Article citation info:
Hoang AD, Vintr Z, Valis D, Mazurkiewicz D. An approach in determining the critical level of degradation based on results of accelerated test. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2022; 24 (2): 330–337, http://doi.org/10.17531/ein.2022.2.14.

An approach in determining the critical level of degradation based on results of accelerated test

Indexed by:
Web of Science Group

Anh D. Hoang[a], Zdenek Vintr[a,*], David Valis[a], Dariusz Mazurkiewicz[b]

[a] University of Defence, Faculty of Military Technology, Kounicova 65, 66210, Brno, Czech Republic
[b] Lublin University of Technology, Mechanical Engineering Faculty, ul. Nadbystrzycka 36, 20-618 Lublin, Poland

Highlights

- Degradation measurement of LEDs in the frame of accelerated tests.
- Method for determination of the degradation threshold based on the failure data.
- Determination of degradation threshold using classical approach.
- Determination of degradation threshold using Wiener Process-based model.

Abstract

Nowadays, systems are more complex and require high reliability for their components, especially critical system components. Therefore, to avoid serious damage, system are often replaced before the actual failure. The replaced parts are considered to have "soft failure", and the limit in which the parts are replaced is known as the critical level of the degradation process. Determining the appropriate value of the critical level for a product is an important problem in their exploitation, as well as for predicting the Mean Time to Failure (MTTF) or Remaining Useful Lifetime (RUL) of this product based on the degradation data by the mathematical models. In this article, an approach in determining the critical levels based on failure data from an accelerated test is introduced. This approach is applied with the degradation process of Light-Emitting Diodes (LED) in an accelerated test and a type of Wiener process-based model is used to predict the MTTF or RUL of LED based on their degradation data and the found critical level.

Keywords

critical level, threshold of degradation process, accelerated test, LED, Wiener process.

1. Introduction

Hard failure is a type of failure in which the product completely loses its ability to perform the required functions of the product. The hard failures for a family of products happen at different times, following a certain random distribution, because there are many random factors that affect product performance [5]. Analyzing the failure data of a product family using the classic method, according to standard IEC 60605-4:2001 [8], gives the mean time to failure (*MTTF*) of the product family. *MTTF* is an important quantity, plays a decisive role in determining the time to replace products of any product family in the preventive maintenance policy, in which the product must be replaced before the time of actual failure. In general, it means that at the time $t < MTTF$. A major disadvantage of the preventive maintenance policy is that it is difficult to determine exactly the time t before the *MTTF*. Especially for critical systems, product replacement is often performed at the time $t << MTTF$, even if the products are still in good technical condition. It increases costs during product utilization. In addition, for highly reliable products, there is a lag of failure data since it takes a long time and high cost to test until failure occurrence.

This disadvantage can be overcome by using the Condition-Based Maintenance Policy, where the technical condition of the product is determined by periodically observing and measuring the parameter, which represents the degradation level of the product. Based on the degradation data, which is composed of measured values of the degradation parameter, a product is considered as "failed" (soft failure or boundary-crossing failures [1, 20]) when the value of the degradation quantity is greater than a predefined critical value (threshold). In this way, the product is only replaced when necessary, thereby utilizing best the product using value.

Due to the randomness of the degradation processes, statistical mathematical modelling methods are used to describe the degradation process and predict the *MTTF* or Remaining Useful Lifetime (*RUL*) of a product based on the degradation data [6, 9, 18]. Some statistical mathematical models, such as the Wiener Process-Based Model, the Gamma Process-Based Model, or the Statistical Regression Model etc. are commonly used to describe and study the degradation process. Some published works using these types of models (Wiener Process-

(*) Corresponding author.

E-mail addresses: AD. Hoang (ORCID: 0000-0001-8846-8537): anhdung.hoang@unob.cz, Z. Vintr (ORCID: 0000-0003-3128-0802): zdenek.vintr@unob.cz, D. Valis (ORCID: 0000-0002-3911-2689): david.valis@unob.cz, D. Mazurkiewicz (ORCID: 0000-0002-9887-8203, d.mazurkiewicz@pollub.pl)

based Model – [10, 12, 17, 21]; Gamma Process-based Model – [2, 15], Statistical Regression Model – [14]) are just a few examples of the several published works related to this problem. In the above works, the *MTTF* or *RUL* of the product is predicted based on the obtained degradation data and based on the degradation threshold of soft failure.

First-passage probability distribution of product is also the research object of several published articles, such as works [11, 19], in which determining the analytic expressions of First-passage probability distribution of product and the calculating the *MTTF* or *RUL* of a product depend significantly on the predetermining of the degradation threshold of product.

In the above-mentioned works, the critical level of the degradation process has just been given for calculation, without explaining how to select these values. Deng et al. [1] shows that the determination of the critical level of a product can be done in two ways: based on expert knowledge or based on data analysis. For complex systems, there exist major limitations of the expert's knowledge about the system. Therefore, data analysis should be used to assist in determining the value of critical level. Deng et al. [1] also provides a method to correct the value of the critical level, where an initial critical level is chosen, and the real value of the critical level is redefined based on the inverse first passage problem and the real degradation data of the product. However, the problem of choosing the right value of the initial critical level for a system is still a problem that must be studied more.

With degradation processes, on basis of corrosion, wear, etc., the value of the critical level can be defined based on the analyst's knowledge about the strength limit of material or structure. With LED, when the light output is used by manufacturers as degradation quantity, the L50 or L70 criteria are used as the critical level to define soft failure (the output light of LED degrades and is equal to 50 % or 70 % of the initial value of new LED) [3, 7]. However, in military vehicles, directly measuring the output light to determine the degradation level of LED is difficult to occur due to the other light sources in the vehicle. Then the voltage measured between two ends of the LED can be used as a degradation parameter to exhibit the degradation of the LED. But how to define the suitable critical level while we do not know the relationship of the voltage with the real failure of LEDs? In such cases, choosing the value of the critical level is really a big challenge.

The article gives an approach to determine the critical levels in degradation modelling based on product failure data. With this approach, the challenge as with LED can be solved. The lack of product failure data, especially with a high-reliability product, can be overcome by using Accelerated Test (AT) with appropriate testing conditions.

In this article, an AT with LEDs is introduced. The failure data of LEDs in this test is used to apply the proposed approach in defining the critical level of LED. Wiener Process-Based Model (WPBM) with measurement errors and unit-to-unit covariates is used to process the degradation data from the experiment, predict the *MTTF* and *RUL* of LED in this test. Based on the defined critical level of degradation (threshold), the data are also processed using the classical method (by standard IEC 60605-4:2001 [8]) to compare with the result by the mathematical statistical model to give the conclusion.

2. Determining the critical level of degradation process

The critical level of the degradation process is determined such that the product is replaced when the degradation quantity exceeds this value, and no real hard failure of the product occurs. For important systems, this value is often determined to be smaller to ensure high system safety. In practice, there exists a small probability, that the hard failure can occur even with a product that has only been working for a short time when the degradation quantity is very small. This is the early "infant mortality" failure of the 'infant mortality' product. Therefore, determining the fair value of the critical value, to ensure that no hard failure occurs is relatively difficult.

The above analysis suggests that it is impossible to determine the critical level so that no hard failure will occur at all, but it is possible to determine the value of the critical level so that there is only a certain probability that a hard failure will occur. This is the statistical significance level α, which means that when the degradation level of the product reaches the degradation critical level, there is α probability that the products show a hard failure.

To determine the threshold of the degradation process with the significance level α, the probability distribution of the failure degradation data of the product must be determined. The first determining method is parametric methods, which means that one of the underlying probability distributions, followed by the failure data, needs to be determined, such as Normal, Exponential, Weibull distributions – the probability distributions commonly used with the failure data. Here the hypothesis test must be done, including testing the normality of data, or testing for other probability distributions. There are many normality test methods: QQ plot, Anderson–Darling test, Kolmogorov–Smirnov test, Lilliefors test, Shapiro–Wilk test etc., in which QQ plot is a graphical visual preliminary test, and the remaining testing methods work on the test statistic. Each of these test methods is based on certain assumptions and when applying them it is always necessary to assess to what extent these assumptions are met in a given case [16]. According to several studies, such as [16], the Shapiro-Wilk test is the best power test for normality, followed by Anderson–Darling, Lilliefors, and Kolmogorov–Smirnov tests, respectively. In addition, the Kolmogorov–Smirnov or Anderson–Darling tests can also be used to test the null hypothesis that the data follow the exponential or Weibull distributions. After determining the probability distribution that the data follow, the parameters of probability density function (PDF) can be determined, thereby finding the critical level of degradation process at significance level $\alpha = 0.05$ or $\alpha = 0.01$ of this probability distribution with these data.

In this case, nonparametric methods are also a powerful method, helping determine the cumulative distribution function (CDF) and PDF with a limited number of assumptions about the underlying distribution of the data. Smoothing methods using a kernel density estimator are motivated by empirical CDF, but it is estimated that it is more efficient and complete than the empirical distribution function of the data [4]. From the found CDF it is possible to determine the *p*-value (at level 0.05 or 0.01 significance) of this probability distribution of these data.

In the final step, from the found CDFs, the critical level of the degradation process at significance level $\alpha = 0.05$ or $\alpha = 0.01$ depending on the importance of the product in the system can be defined.

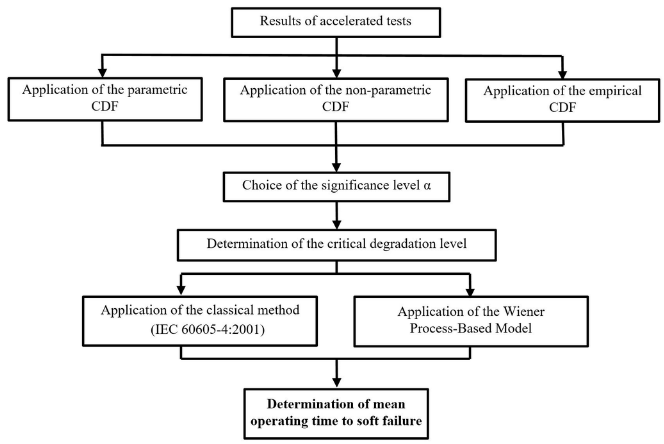

Fig. 1. The main steps of the mean time to soft failure determination process

3. An accelerated test with LEDs

In order to determine the critical degradation level, information on the changes of the parameter that characterises the degradation level as a function of the operating time of items under test and the operating time to failure of the items is necessary. The object of investigation in the presented case were 10W 700LM/90° white LEDs and an accelerated reliability test of these LEDs was used to obtain the necessary information. Increased temperature was used as an accelerating factor in the test and the LEDs were tested in a climate chamber at 90 °C. In the first case the LEDs were periodically switched on and off (ON/OFF mode) and in the second case they were permanently switched on (ON mode). The main objective of the experiment was to obtain information about the degradation process in the case when the LEDs are operated in ON/OFF mode and to compare the intensity of degradation in this mode with the intensity of degradation when the LEDs are permanently switched on. In both cases, the LEDs were supplied with a nominal (maximum allowable) current I_f = 1.05 A. Fig. 2 shows the time profile of switching the LEDs operating in ON/OFF mode. The LEDs were always on for 30 seconds and then off for 30 seconds, and this cycle was repeated periodically.

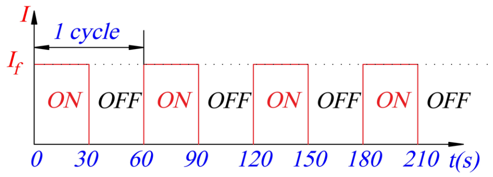

Fig. 2. Time profile of switching the LEDs operating in ON/OFF mode

Since the magnitude of the supply current affects the load level of the LEDs, this aspect was also investigated in the experiment. Thus, in ON/OFF mode, two more groups of LEDs were tested at two different power supply current levels lower than the nominal current. Table 1 summarizes the number of LEDs tested and the conditions under which they were tested. The chosen test conditions were determined with respect to their expected real operating conditions. A discussion of the whole procedure for determining the test conditions and an explanation of the technical and economic constraints that had to be respected in the test design is beyond the scope of this article and can be found in the work [13].

Table 1. Quantity, loading current, and testing modes of the LED groups

Quantity (LEDs)	Loading current I_f (A)	LED operating mode	Climate chamber
20	1.05	ON/OFF	Votsch VC3 7034
5	0.95	ON/OFF	Votsch VC3 7034
5	0.85	ON/OFF	Votsch VC3 7034
10	1.05	ON	Votsch VT 4004

The overall arrangement of the experiment can be seen in Fig. 3 and the arrangement of the test and measurement equipment in the laboratories in Fig. 4. Two climatic chambers were used for the implementation of the accelerated test. The Votch VC3 7034 chamber was used to test LEDs operating in ON/OFF mode and the Votch VT 4004 chamber was used to test LEDs operating in ON mode. Constant temperature is maintained in both chambers using the built-in automatic control and monitored by the PT-100 temperature sensors. All LEDs are powered by High-Precision Digital DC Power Units Keysight E3634A. Each power unit always supplies 5 LEDs with a constant current of the magnitude shown in Table 1. For LEDs operating in ON/OFF mode, the power units also provide cyclic power switching in accordance with the timing profile shown in Fig. 2.

For the purpose of the test, the LEDs were installed on aluminium plates, each with 10 LEDs. The individual LEDs are connected to the measurement system in such a way that the voltage at the terminals of each LED can be periodically measured. The method of connecting the individual LEDs to the power supply and to the measurement system is shown in Fig. 5. Voltage measurement on individual LEDs is provided using the Keysight 34980A Multifunction Switch Measurement Unit. Measurements are taken periodically, every 10 minutes when all LEDs are switched on. Fig. 6 shows the placement of the individual LED boards in the Votch VC3 7034 climate chamber and the wiring of the individual LEDs.

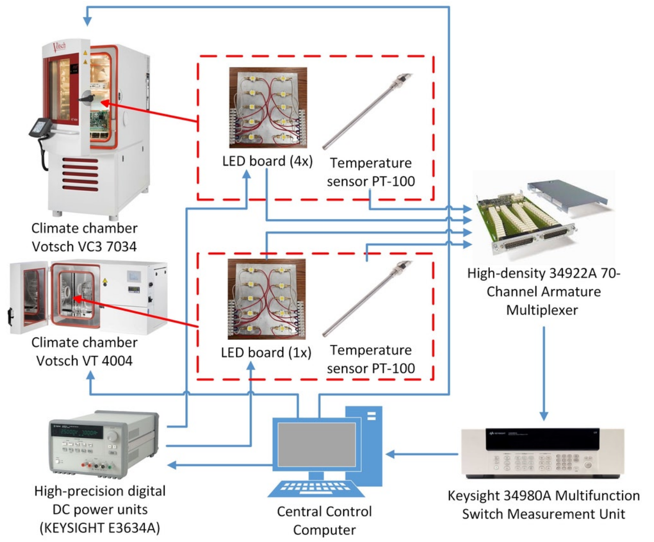

Fig. 3. Overall arrangement of the experiment

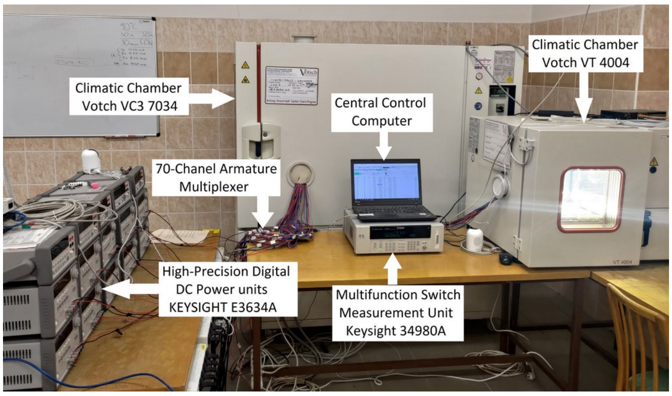

Fig. 4. Arrangement of test and measurement equipment in the laboratory

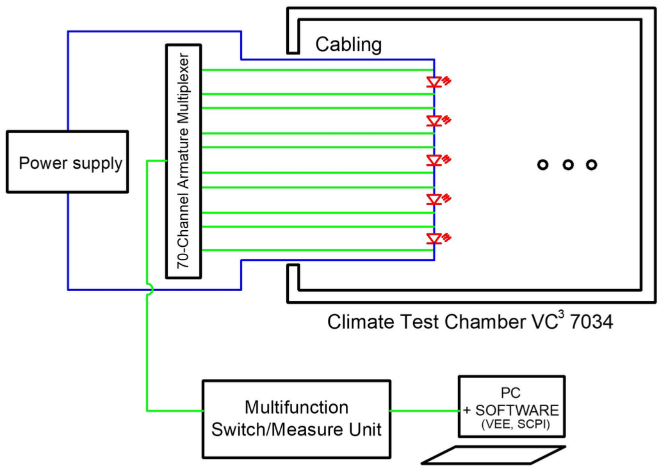

Fig. 5. Scheme of the power supply and voltage measurement on individual LEDs

Fig. 6. Placement of the individual LED boards in the Votch VC3 7034 climate chamber

Currently, only the first part of the presented experiment has been completed, which consisted in testing the LEDs in the ON/OFF mode when supplied with maximum current. All 20 LEDs tested have already experienced a hard failure and a complete data set is available. Therefore, this paper focuses on the evaluation of this data.

Testing of the remaining LEDs is currently still in progress. In the group of LEDs operating in the ON/OFF mode when powered at lower than nominal current, several failures have already been recorded, but most of the tested LEDs are still functional. In the group of LEDs operating in ON mode, all tested LEDs are still functional. The end of the experiment and its comprehensive evaluation is expected after all tested LEDs operating in ON/OFF mode have failed.

4. The results of the experiment

The degradation process of 20 LEDs mentioned in Section 3 is shown by the voltages measured in the test. The changes of measured voltages of 20 LEDs from the accelerated test are shown by the graphs in Fig. 7, where the numbers 1, 2, 3, ... 19 and 20 indicate the individual diodes tested. The graph of LED nr. 8 is shown separately in Fig. 8 and Fig. 9 to clearly show the change of measured voltage in the LED degradation process.

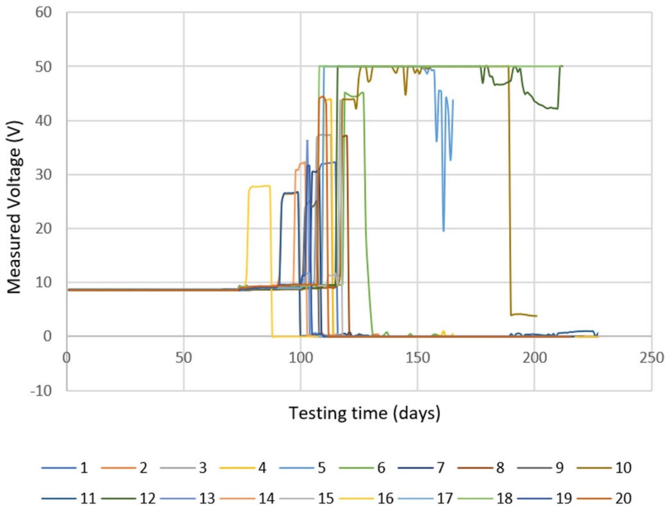

Fig. 7. The graphs of the measured voltages of the LEDs from the accelerated test

From the graphs showing the voltage of the LEDs in Fig. 7 and Fig. 8, the degradation process of all 20 LEDs follows the same rule. Firstly, the initial measured voltage current of 20 LEDs is about 8.6 V. According to the degradation level of the LEDs, this voltage gradually decreases. These decreases are quite small so they cannot be seen in Fig. 7 and Fig 8. Fig. 10 show the voltage changes of LED 1008 in the first stage (from the beginning of the test to the first voltage jump), where small decreases in voltage can be seen. After a long testing

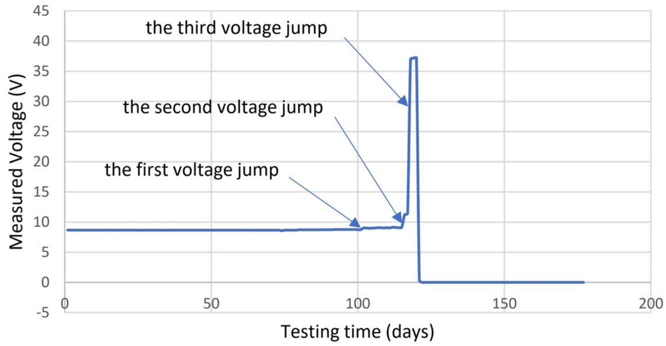

Fig. 8. Diagrams of the measured voltages of LED nr. 8

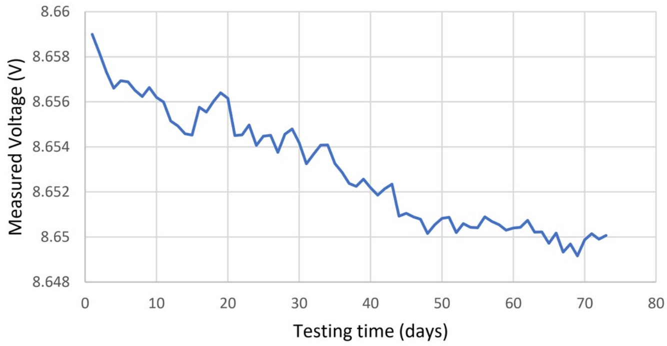

Fig. 9. Diagrams of the voltages measured from LED nr. 8 from the beginning of the test to the first voltage jump

time, the voltage jump of the LEDs takes place and the LED voltage value gets to a voltage level greater than 9V (the specified voltage is dependent on the LEDs. At a voltage level greater than 9V, the light output of the LEDs decreases clearly. The voltage value (greater than 9V) continues to decrease as the LEDs degradation trend. After a short time, for some LEDs, a second voltage jump happens and reaches a value greater than 20V or 50V, then the LEDs are completely damaged and do not light up. With some LEDs, the LED voltage jumps to an intermediate voltage value greater than 11V and then jumps to a voltage greater than 20V or 50V, the LEDs completely fail. Three voltage jumps of LED nr. 8 can be observed in Fig. 8. Thus, the LEDs degradation process might be considered as multistage. This is understandable, given the complex structure of LEDs and the diverse failure mechanisms of LEDs, as detailed in [2].

The operating time of LEDs at voltage levels greater than 9V or 11V is relatively short compared to the entire operating time in the ON operating mode of the accelerated test. So, when one observes that the voltage of the LEDs reaches a value greater than 9V, it can be concluded that the hard failure of the LED is about to occur.

The degradation parameters in this test can be directly the measured voltage of LEDs U, which decreases in any certain degradation stage of LED, or the voltage difference, ΔU, which is calculated by subtracting the measured LED voltage at any moment from the measured voltage at the initial moment. The voltage difference, ΔU, is increasing and positive quantity and is often used as a degradation parameter in mathematical models of the degradation process.

In this test, the voltage value of an actual hard failure of LEDs can be measured after the second or the third jump has taken place. At this moment, the voltage difference calculated by the above way obtains a negative value, because two voltage values are measured in different stages. This measured voltage has no sense in determining the threshold of voltage difference for the one-stage degradation model, but can be used with the multistage degradation model. This issue is not addressed within the scope of this article.

In this case, the only voltage value right before the first jump is proposed as the degradation value of the hard failure of the LEDs. Table 2 presents the voltage difference ΔU measured at the time of the

Table 2. *Data on hard failures of LEDs in ON/OFF modes with loading currents I_f =1.05A*

LED nr.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Degradation level ΔU (V)	0.0089	0.0108	0.0086	0.0099	0.0074	0.0089	0.0104	0.0098	0.0084	0.0082
Time to failure (day)	68	76	76	78	68	76	64	73	76	71
LED nr.	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Degradation level ΔU (V)	0.0102	0.0109	0.0095	0.0082	0.0104	0.0097	0.0105	0.0098	0.0097	0.0097
Time to failure (day)	72	72	68	68	68	72	68	51	68	68

hard fault (defined in this way) for diodes tested in ON/OFF operating mode with loading currents I_f=1.05 A.

5. Determining the critical level of LEDs degradation process in accelerated test

First, the parametric method of probability distribution determination is used. In Fig. 10, the Q-Q plot of the hard failure data of the LEDs is shown. By this figure, we can see that the data relatively follow a normal distribution.

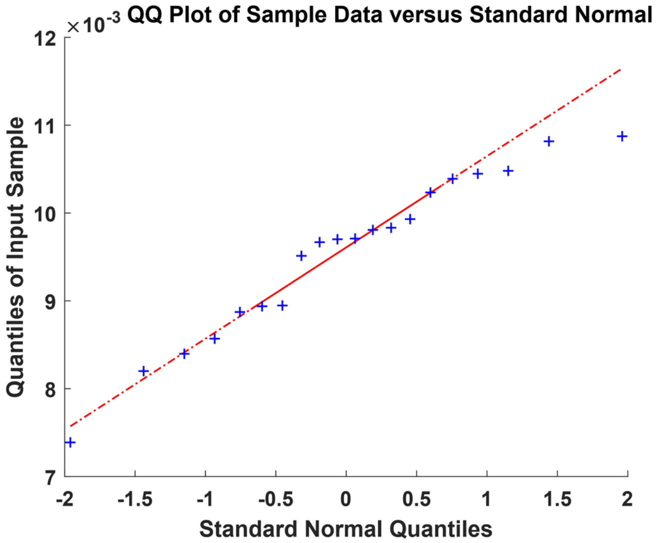

Fig. 10. The Q-Q plot of the data of hard failure of LEDs

In the following step, the hypothesis tests for normality were carried out using MATLAB software. The results of different hypothesis tests are given in Table 3.

Because the sample size (20 LEDs) is not big enough, and the Anderson–Darling and Lilliefors test was concluded to be more effective than the Kolmogorov–Smirnov test, it can be concluded that the hard failure data of LEDs follow the normal distribution and the parameters of the normal distribution of these data can be calculated. In this case, the mean and variance of the normal distribution are 0.0094 and $9.2 \cdot 10^{-7}$, respectively.

In the next step, nonparametric methods including the empirical CDF and nonparametric CDF by smoothing methods using a kernel density estimator – are applied. The result can be shown in Fig. 11.

The last step is to find the critical level of the degradation process ΔU_{crit} at the selected significance levels α = 0.05 and α = 0.01 of the above found CDF. The results are given in Table 4.

Table 3. *The results of different hypothesis tests using the MATLAB software*

Hypothesis test	**Results**
Anderson–Darling	Fails to reject the null hypothesis
Lilliefors	Fails to reject the null hypothesis
Kolmogorov–Smirnov	Rejects the null hypothesis

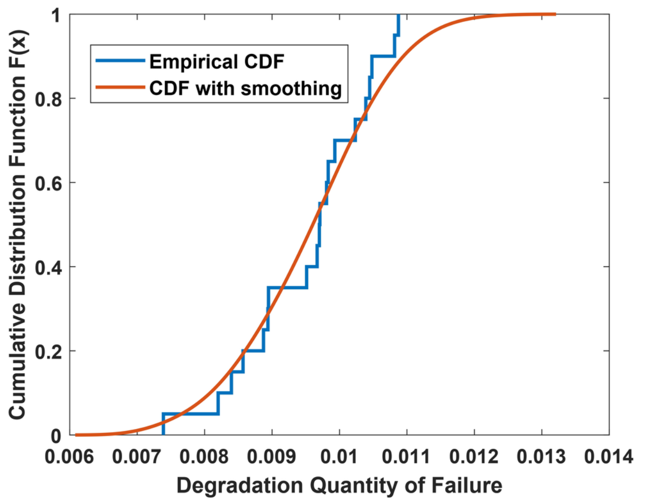

Fig. 11. The graph of CDF of the data using nonparametric methods

Table 4. *The critical level of the degradation process determined by different determining methods*

Determining method	The critical level of degradation ΔU_{crit} at the significance level α = 0.05 (V)	The critical level of degradation ΔU_{crit} at the significance level α = 0.01 (V)
Normal distribution	0.0081	0.0074
Empirical CDF	0.0078	0.0074
Nonparametric CDF with smoothing	0.0076	0.0069

6. Evaluating experiment data by the classical method - IEC 60605-4:2001

In this section, with the critical level ΔU_{crit} = 0.0074 V, based on the degradation data from the accelerated test with LEDs, the soft failure data of LEDs are calculated and given in Table 5. These data are used to calculate the *MTTF* of LED using the classical method - IEC 60605-4:2001 [8].

To use the standard IEC 60605-4:2001, we assumed that the soft failure time of LEDs follows an exponential distribution with constant failure intensity. The experiment ends when all of the LEDs have soft failures.

Table 5. Data on soft failure of LEDs in the ON/OFF operating modes with loading currents I_f =1,05 A

LED nr.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Time to soft failure (day)	62	43	47	47	68	47	39	43	64	49
LED nr.	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Time to soft failure (day)	36	35	43	44	43	43	37	36	43	36

The cumulative test time T^* is calculated by:

$$T^* = \sum_{i=1}^{n} t_i \tag{1}$$

where t_i – the time to soft failure of i-th LED in the experiment and T^* = 905 days.

Because all of the LEDs in this experiment have soft failures, the number of failures in the experiment is r = 20.
According to IEC 60605-4:2001, the *MTTF* for the soft failure of LEDs in this mode of the experiment is:

$$MTTF = \frac{T^*}{r} = 45.25 \text{ days} \tag{2}$$

The lower and upper limit of the two-sided confidence interval of the *MTTF* – $MTTF_{L2}$ and $MTTF_{U2}$ – for the soft failure of LEDs is calculated by equations (3) and (4):

$$MTTF_{L2} = \frac{2T^*}{\chi^2_{1-\alpha/2}(2r)} \tag{3}$$

$$MTTF_{U2} = \frac{2T^*}{\chi^2_{\alpha/2}(2r)} \tag{4}$$

where $\chi^2_{1-\alpha/2}(2r)$ is the chi-squared distribution with the number of degrees of freedom $2r$ at the confidence level ($1-\alpha$).

Table 6. The values of MTTF and its confidence intervals at the confidence level 90 %

The critical level of degradation ΔU_{crit} (V)	***MTTF* (day)**	**$MTTF_{L2}$ (day)**	**$MTTF_{U2}$ (day)**
0.0081	51.6	37.02	77.86
0.0078	49.55	35.55	74.76
0.0076	45.9	32.93	69.26
0.0074	45.25	32.46	68.28
0.0069	41.6	29.84	62.77

Using these relationships, the *MTTF* (soft failure) and its confidence intervals were calculated for the individual degradation levels given in Table 4. Confidence level 90 % was considered in the calculation. The results of the calculations are presented in Table 6.

7. Evaluating experiment data by mathematical model - Wiener Process-Based Model with measurement errors and unit-to-unit covariates

In this Section, the degradation data measured before the moment, when the first hard failure happens, are evaluated by the mathematical model - Wiener Process-Based Model with measurement errors and unit-to-unit covariates. With this model, the degradation data and the critical level determined above are utilized to predict the *MTTF* for the soft failure of the LEDs.

Wiener Process-Based Model (WPBM) with measurement errors and unit-to-unit covariates is used in works [1, 12, 17, 21]. The degradation data set with n objects and m observations for each object can be described by WPBM, as in the following equation (5):

$$y_{ij} = x(t_{ij}) + \varepsilon_{ij} = \mu_i \Lambda(t_{ij}) + \sigma B(\tau(t_{ij})) + \varepsilon_{ij} \tag{5}$$

where y_{ij} and $x(t_{ij})$ – the measured degradation value and the true degradation value of the i-th object at the time t_{ij}, respectively. The true degradation increments $x_{i1}, x_{i2} - x_{i1}, x_{i3} - x_{i2}, \ldots x_{im} - x_{i(m-1)}$ are assumed independent of each other and follow a normal distribution with mean $\mu_i [\Lambda(t_j) - \Lambda(t_{j-1})]$ and variance $\sigma^2 [\tau(t_j) - \tau(t_{j-1})]$; $B[\Lambda(t_{ij})]$ – a Brownian motion; ε_{ij} – measurement errors, that follow a normal distribution $\varepsilon_{ij} \sim N(0, \sigma_\varepsilon^2)$ and are independent of each other and of the true degradation value $x(t_{ij})$; μ_i – drift parameter; σ^2 – variance parameter; $\Lambda(t_{ij})$, $\tau(t_{ij})$ – the time-scale transformation functions, that can follow the different laws, including linear law $\Lambda(t) = at$, the Power-law $\Lambda(t) = e^{at}$ or exponential law $\Lambda(t) = t^a$, a – an unknown fixed coefficient.

To remove subscript i from the time notation, assume that the degradation values are measured at the same times for all units. The equation (5) can be rewritten in the matrix form:

$$\mathbf{y}_i = \mu_i \Lambda + \sigma B(\boldsymbol{\tau}) + \boldsymbol{\varepsilon} \tag{6}$$

where the vector and matrix are denoted by a bold symbol and:
$\mathbf{y}_i = (y_{i1}, y_{i2}, \ldots y_{im})$' – vector of the degradation values of i-th object at the time $\mathbf{t} = (t_1, t_2, \ldots t_m)$' where $t_1 < t_2 < \ldots < t_m$ – vector of observation time;
$\boldsymbol{\varepsilon}$ – vector of measurement errors; $\boldsymbol{\Lambda}$ $[\Lambda(t_1), \Lambda(t_2), \ldots \Lambda(t_m)]$' and $\boldsymbol{\tau}$ = $[\tau(t_1), \tau(t_2), \ldots \tau(t_m)]$' are the vectors of the time-scale transformation functions.

$\mathbf{y}_i = (y_{i1}, y_{i2}, \ldots y_{im})$' follows a multivariate normal distribution with mean $\mu\boldsymbol{\Lambda}$ $[\mu\Lambda(t_1), \mu\Lambda(t_2), \ldots \mu\Lambda(t_m)]$' and covariance matrix $\boldsymbol{\Sigma}$ with its ij-th elements defined in equation (7):

$$\Sigma_{ij} = \mathrm{cov}(Y_{ij}, Y_{ik}) = \begin{cases} \sigma^2 \tau(t_j) + \sigma_\varepsilon^2 & j = k \\ \sigma^2 \min\left(\tau(t_j), \tau(t_k)\right) & j \neq k \end{cases} \tag{7}$$

μ is assumed to be different between different units, and is normally distributed, $\mu \sim N(\mu_0, \sigma_0^2)$, which shows the unit-to-unit variate in the mathematical model. Then $\mathbf{y}_i = (y_{i1},$

y_{i2}, …. y_{im})' follows a multivariate normal distribution with mean $\mu_0\mathbf{\Lambda}'$ and covariance matrix $\mathbf{\Sigma} = \mathbf{\Omega} + \sigma_0^2\mathbf{\Lambda\Lambda}'$, where:

$$\mathbf{\Omega} = \sigma^2\mathbf{Q} + \sigma_\varepsilon^2\mathbf{I}_m; \text{ and } \mathbf{Q} = \begin{bmatrix} \tau(t_1) & \tau(t_1) & \cdots & \tau(t_1) \\ \tau(t_1) & \tau(t_2) & \cdots & \tau(t_2) \\ \vdots & \vdots & \ddots & \vdots \\ \tau(t_1) & \tau(t_2) & \cdots & \tau(t_m) \end{bmatrix} \quad (8)$$

where $\mathbf{I}_m$ is an identity matrix.

According to [17], the *MTTF* can be calculated by equation:

$$MTTF = \Lambda^{-1}\left(\frac{\Delta U_{crit}}{\mu_0}\right) \quad (9)$$

where ΔU_{crit} – the predefined critical level of degradation.

The parameters of this model are estimated by the Maximum Likelihood Method (MLE), including getting the first partial derivatives of the total Log-likelihood function, setting them equal to zero to make the equations system, and solving this system to find the unknown model parameters. To reduce computational burden, a three-step computing method has been introduced and used effectively for WPBM in the works [1, 17, 21].

In this article, the exponential law of time-scale transformation functions $\Lambda(t) = \tau(t) = t^a$ is selected. In this case, the experimental time of the degradation data was determined one day earlier than the time when the first hard failure in the 20 LEDs is observed. Based on WPBM with measurement errors and unit-to-unit covariates, the WPBM model parameters of WPBM, defined by the three-step computing method, and the *MTTF* (soft failure) of the LEDs, calculated by Equation (9) with different determined thresholds (see Table 4), are given in Table 7.

Table 7. MTTF (soft failure) of LEDs calculated using WPBM with different determined thresholds

ΔU_{crit} (V)	*MTTF* (day)
0.0081	51.14
0.0078	48.77
0.0076	47.21
0.0074	45.66
0.0069	41.82

8. Discussion

The presented method allows prediction of the mean time to soft failure for LEDs with pre-selected confidentiality level. However, knowledge of the degradation process model is necessary for the application of the procedure. To create it, the authors use the results of accelerated tests of LEDs, which allow obtaining the information needed to create a degradation model in a relatively short time. The degradation model itself then allows the prediction of the mean useful technical lifetime of the LED in terms of mean time to soft failure. Knowing the dependence of the degradation level on the operating time also allows continuous assessment of the technical condition of the LED (its degradation level) and prediction of the remaining useful lifetime by relatively simple measurement of the voltage changes at the diode terminals. The proposed method thus creates conditions for ensuring high operational reliability of the system using LEDs, because it allows to determine quite efficiently the time at which it is necessary to carry out preventive LED replacement and thus prevent the occurrence of a hard failure.

The key step of the method is to determine the critical level of degradation that corresponds to the occurrence of a soft failure. For this purpose, the results of a corrugated test of 20 LEDs are used in this paper. The relatively low number of LEDs tested was due to technical (size of the climate chamber, capacity of the measuring apparatus, available power junctions etc.) and economic constraints. A higher number of LEDs tested would undoubtedly increase the credibility of the results obtained.

The obtained data were evaluated using normal distribution of empirical CDF and non-parametric CDF with smoothing. The levels of critical degradation determined by each method do not differ much from each other. The differences in the determined values are in the range of 6-7 % depending on the chosen level of confidence. All the methods used allow the determination of the critical degradation level with the chosen level of significance. The application of non-parametric CDF with smoothing seems to be the most appropriate evaluation method, as it does not require the determination of any specific type of distribution (parametric) and testing its validity, while providing a continuous CDF.

To determine the mean time to soft failure (at a given level of critical degradation), the authors propose two methods. The so-called classical method based on statistical processing of the experimental results according to the recommendations of the international standard IEC 60605-4:2001 and the method based on the application of WPBM with measurement errors and unit-to-unit covariates. Both methods allow the estimation of the MTTF for a selected level of critical degradation. The results of the calculation by both methods are practically identical (within 1 % of each other). The inherent advantage of the classical method is that it allows not only to perform a point estimate of the MTTF, but also to determine the MTTF confidence intervals with the selected confidence level, whereas the WPBM application does not provide this option. Taking this into account, it is therefore preferable to use the classical method, which is also considerably simpler in terms of application.

9. Conclusions

The paper presents the proposal of a method for modelling the LED degradation process allowing to predict the occurrence of failures and to determine the remaining useful life of the LED based on the detected degradation level. The method uses the results of accelerated tests of LEDs as input information. However, analogically, the results of monitoring the degradation process of LEDs in normal operation can also be used to build the model. The proposed method, among other things, allows the determination of a critical level (threshold) of the degradation process (soft failure) beyond which we can expect the occurrence of a hard failure (complete loss of function). The knowledge of such a degradation threshold value enables an effective application of Condition-Based Maintenance Policy and a practical estimation of the remaining useful life of the LED (remaining time to soft failure) in real operation.

However, the presented method is not only designed for the needs of degradation assessment in LEDs. In designing the method, generally valid principles and procedures have been applied, which are fully applicable wherever the level of degradation can be measured accurately using appropriate parameters. Therefore, the authors anticipate that the proposed method can be used to determine the critical degradation level, predict the occurrence of failures and estimate the remaining useful life not only for LEDs but also for other types of objects. Verification of the above assumption is the main objective of future research work. The intention is to verify the applicability of the proposed procedures for determining the critical degradation level both for other types of electronic components and for selected electromechanical and mechanical components.

A further aim is to verify the practical applicability of the proposed method for degradation assessment and estimation of the remaining useful life of LEDs in normal operation, where problems can be expected especially with the implementation of voltage measurements at the LED terminals, since a constant value of the supply current and corresponding measurement accuracy must be ensured. The solution of these problems is the main limiting factor for the use of the proposed method in monitoring and evaluation of LEDs degradation in normal operation.

Acknowledgement

This article has been prepared with the support of the Ministry of Defence of the Czech Republic – Project for the Development of the Organization „DZRO Military autonomous and robotic systems“ and Specific Research Project "SV22-202 Development and research of technologies for evaluating the properties of military ground vehicles".

Research co-financed by the Scientific Discipline of Mechanical Engineering (Lublin University of Technology, grant nr FD-20/IM-5/072).

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