A method for online detection and lifespan evaluation of light sources

YU Kanghua, CHEN Huacai*, **ZHU Zhouhong, HU Jinzhao, and CHEN Yongming**
College of Optical and Electronic Technology, China Jiliang University, Hangzhou 310018, China

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Light emitting diode (LED) light source degradation detection and lifetime evaluation usually use the data of light flux change as a basis, but the process of light flux measurement is complicated and tedious, requiring the use of an integrating sphere, and cannot be performed online. This is unfriendly to the detection of machine vision light sources used in production lines. To address this problem, this paper proposes and designs a method for online detection and lifetime evaluation of light sources by using a mini spectrometer to detect the intensity of light sources online, and evaluates the light degradation and lifetime of light sources based on the changes in light intensity during use. This determines whether the light source needs to be adjusted or replaced, avoiding misjudgment or missed judgment in production detection due to light source degradation. The experiment was conducted on LED under high-temperature accelerated aging. The light intensity data after aging was fitted by an acceleration and life evaluation model, and the fitting result showed that the error of life evaluation by this method was 8.37%. As a comparison, this paper also detects the changes in light flux of light sources during the experiment, and the average error between the decay of light intensity and the decay of light flux was only 0.102%. It has been validated that the error in evaluating the lifetime of light sources using this method is 10.71%, and the accuracy of the evaluation is about 90%. The results show that the method is accurate, reliable, and can be used as a basis for online detection and evaluation of LED light source degradation.

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In modern production lines, online product packaging and quality inspection are often achieved through image detection methods. Lighting is a crucial component in machine vision systems[1] and directly affects the quality of image acquisition, which is the key factor determining the accuracy of visual inspection. Light emitting diode (LED) lights are commonly used as the lighting source in production lines due to their high brightness and stability[2], but they also have a serious problem of light decay[3]. To ensure the imaging quality and stability of detection, it is necessary to regularly check the lighting sources in production and evaluate their light decay and remaining lifespan, to avoid affecting the accuracy of product inspection results and causing quality issues.

Light decay refers to the phenomenon of reduced light output over time of a light source. It is an important consideration in terms of the life and performance of the light source. For LED light sources, the degradation of phosphor performance and aging of encapsulation materials are the main reasons for light decay[4,5]. In addition to its own factors, light decay is also affected by environmental conditions, such as temperature, humidity, and pollution. These factors will accelerate the aging of the light source to different degrees, so the requirements of the operating environment for the light source are also an important factor in light decay assessment.

The degradation of a light source is usually based on the change in its luminous flux[6]. In most cases, the light source is considered to be failed when its luminous flux decreases to 70% of the initial light output[7]. However, the light output needs to be measured using an integrating sphere, and the measurement requires separating the light source, which is a complex and cumbersome process. As a result, the continuity of product testing on the production line may also be affected to some extent. Currently, most methods for detecting light sources involve using integrating spheres or other equipment before the light source is manufactured. The light source must also undergo accelerated aging, and monitoring can only be done during the aging process to assess the overall life of the light source. There is little research on real-time detection of light sources during use[8-15].

The spectrum of a light source can reflect the light intensity information, and light intensity can also be used as a criterion for light attenuation. The light source is collected by a spectrometer, which can be developed

* E-mail: huacaichen@cjlu.edu.cn

based on various small spectrometers and embedded in the detection system. The spectral detection can be performed online, and the operation is simple and almost does not affect production. Therefore, to reduce the impact of light source light decay in actual production detection and the inconvenience of light source detection on the production line, this paper designs a probe for online spectral detection and studies the light attenuation and life of LED light sources based on their spectra. Based on the detection of the light intensity change of the light source during use, the light decay and life of the light source are evaluated, making it convenient to adjust and replace the light source in a timely manner and reduce the impact on products' production and quality.

Machine vision systems on production line are spatially closed and narrow, so detecting the light source online in this space requires the spectrometer to be small in volume, light in weight and easy to integrate into the vision system. In response to these requirements, a spectral probe was developed based on the C12666MA spectrometer, as shown in Fig.1. C12666MA is a Hamamatsu's micro spectrometer developed based on MEMS and image sensor technology. Due to the use of a newly designed optical system, the volume and weight are greatly reduced. The spectral response range of the spectrometer is 340—780 nm, with a maximum resolution of 15 nm. The visual light source on the production line is mostly a pulsed light source. The spectrometer may not be able to capture the moment of lighting, so a photodiode was added to the probe to collect the trigger signal of the light source. After integrating the photodiode and C12666MA, the spectral probe has a volume of 96 mm×29 mm×25 mm and a weight of 50 g. The light spectrum data collected by the probe can be transmitted to a PC or tablet computer through an RS485 serial port or USB for visualization. The probe completely meets the requirements for online detection of light sources on the production line.

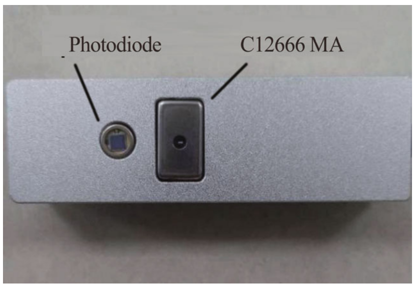

Fig.1 Spectrum probe based on C12666MA

The experiment selected three LED bulbs with the same model and specifications, with a wavelength of 532 nm, a luminous flux of 130 lm, and a power of 1 W (light sources 1—3). The time used to reduce the luminous flux of the LED light source to 70% of the initial value was defined as the standard life of the LED light source. Stress factors that can be used as light source aging include temperature, current, humidity, etc. Taking into account that in practical use, current, humidity and other stresses' levels are nearly constant and rated. Temperature has a larger impact on aging during light source use and it is easier to control among the stress factors. Considering all acceleration stress factors[16-18] and other factors, the experiment finally takes temperature as a constant single accelerated stress factor.

The experiment used an aging box to simulate the operating temperature of the light source. The temperature of the aging box was set to 200 ℃ and the LED light sources were illuminated and placed in the aging box for accelerated aging. The spectral measurement of the light source was performed using a spectrometer every 100 h. The spectrometer was placed 5 cm in front of the light source and the position of the light source and spectrometer was fixed using a fixture to ensure that the relative position of the light source and spectrometer remained unchanged during each measurement. The light intensity of the LED light source at each time point was recorded until the light source decreased to 70%, as shown in Tab.1.

Tab.1 Relative light intensity change of LED after aging at 200 °C

Time (h)	Source 1	Source 2	Source 3	Average
0	1 563	1 560	1 541	1 554.7
100	1 467	1 478	1 450	1 465
200	1 421	1 432	1 414	1 422.3
300	1 376	1 375	1 370	1 373.7
400	1 333	1 368	1 324	1 341.7
500	1 292	1 395	1 286	1 324.3
600	1 259	1 283	1 250	1 264
700	1 212	1 296	1 201	1 236.3
800	1 175	1 193	1 166	1 178
900	1 138	1 179	1 124	1 147
1 000	1 102	1 118	1 094	1 104.7
1 100	1 068	1 142	1 053	1 087.7

The international lighting organization conducted tests on LED light decay under normal working conditions and analyzed a large amount of data to conclude that the light decay follows an exponential model[19]. The formula for the model is given in Eq.(1), where $\varPhi$ is the luminous flux of the light source, and α is the light decay coefficient.

$$\varPhi = \varPhi_0 \exp(-\alpha t). \tag{1}$$

Since the proportionality between luminous flux and intensity remains constant under constant conditions, the experimental data of the light intensity can also be fitted using Eq.(1). The average of the three sets of data was taken and the fitting result is shown in Fig.2.

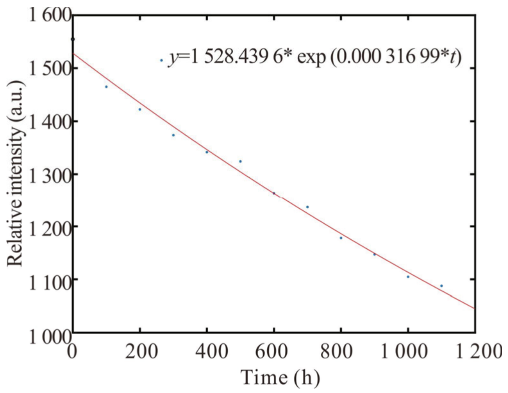

Fig.2 Light intensity fitting curve of LED after aging at 200 °C

The fitting results show that I=1 528.439 6exp(−0.000 316 99t). The model has a good fitting effect, with a small sum-square error (*SSE*) value of 2 136, R-square of 0.991 1, adjusted R-square of 0.990 2 and root mean squared error (*RMSE*) of 14.61. These results indicate that the model has a low error and high correlation with the real data, and the model is reliable. According to the fitting results, the decay rate of the LED light source at 200 °C is 3.17×10^{-4}.

The above calculation result is the life model of the light source under 200 °C, and the final result we want to obtain is the life model of the light source under normal working conditions at room temperature. Therefore, we need to calculate the mathematical relationship between the accelerated stress temperature T and the decay coefficient α. The Arrhenius model (Eq.(2)) shows the relationship between the temperature and the change of the rate constant of the chemical reaction in simple reactions[20]. The relationship between the decay factor and temperature of the light source at different temperatures can be described by

$$\alpha = A\exp(-\frac{E_a}{kT}), \qquad (2)$$

where A represents the pre-factor, E_a represents the activation energy, k is the Boltzmann constant, and T is the thermodynamic temperature. When substituting 473.15 K and 298.15 K into T, the model calculates the decay factor α at 25 °C to be 7.87×10^{-6}. Based on this, the lifetime model of the light source at 25 °C can be calculated, and the use time when the light output decreases to 70% is 5.37×10^{4} h. The average life of this batch of LED light sources at 25 °C was 4.96×10^{4} h, based on actual testing. The error of life evaluation by the intensity detection and model calculation is approximately 8.37%, indicating that the method is relatively reliable for evaluating the life.

In order to further verify the reliability of the method, the experiment compared the accuracy of light intensity detection and the difference between light intensity detection and light source luminous flux in evaluating the life of the light source. The luminous flux of LED lights at the same time point was also detected, and the luminous flux retention rate of the light source was compared with its light intensity retention rate after normalization, as shown in Fig.3.

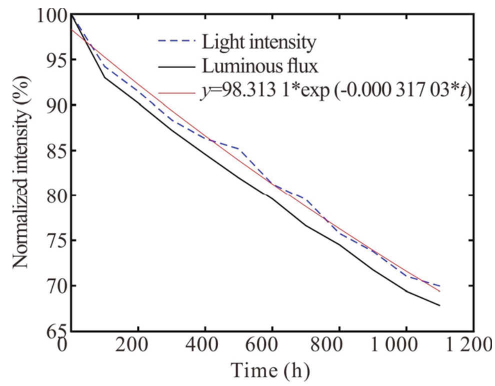

Fig.3 Decay of light intensity and luminous flux of LED after aging at 200 °C

According to Fig.3, throughout the test, the LED light source light intensity and luminous flux measured in the experiment are almost identical, with the decline in light intensity being slower than the decline in luminous flux and the stability of the change being slightly worse. This may be due to interference from some environmental light and other factors during the measurement of light intensity, as well as the lower accuracy of the spectrometer. The measurement of luminous flux is carried out in the integrating sphere, with minimal interference from external factors. Using the luminous flux retention rate as the basis for judging the degree of light source decay, the error in the light intensity retention rate at each time point is less than 0.15%, with an average error of 0.102%. This error is inevitable in production inspection, but is completely within acceptable limits in actual inspections. The results indicate that the spectrometer is accurate in measuring light intensity and that the method of online evaluation of light decay and life by light intensity has strong reliability.

In order to verify the accuracy of the method for online evaluation of the lifetime of light sources, an additional set of validation experiments was conducted based on the above experiments. The validation experiment placed the light source under accelerated aging at a temperature of 250 ℃. Similarly, every 100 h, the light intensity of the light source was detected using a spectral probe, and the light maintenance rate of the light source at each time point was calculated and compared with the light maintenance rate calculated by the model. The decay curve model of the light source at 250 ℃ was calculated as Eq.(3), and the comparative results are shown in Fig.4.

$$\Phi = \Phi_0 \exp(-5.788\times10^{-4} t). \qquad (3)$$

From Fig.4, it can be seen that the decay trend of the actual detected light intensity is basically consistent with the theoretical model. According to the data in the figure, the maximum error between the measured light intensity and the estimated value of the theoretical model at each time point is 2.56%, the minimum error is 0.71%, and the average error is 1.62%. The actual failure time of the light source can be calculated to be around 660 h based on the actual detected light intensity value, while the theoretical failure time of the light source is 616 h, resulting in an error of 10.71% in the overall assessment of the lifetime of the light source. The data above indicates that the theoretical and actual values of the light maintenance rate and the lifetime of the light source have a small error, which overall supports the feasibility of this method for evaluating the lifetime of light sources.

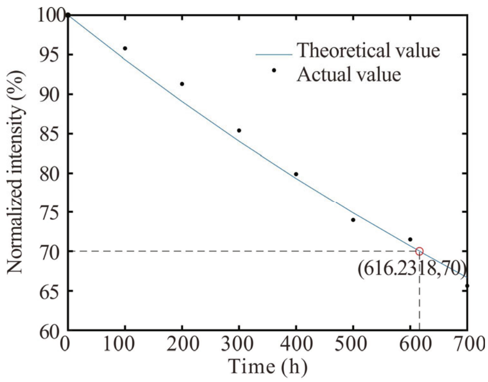

Fig.4 Theoretical light intensity and actual light intensity of the LED after aging at 250 °C

The paper present a method for online detection of LED light source degradation and life assessment by analyzing its spectrum, compared to the traditional method of detecting light flux. The new method is simple and convenient, and can perform online detection on the production line, ensuring the continuity of production testing. Although the spectral detection is easily influenced by environmental light and other external factors, resulting in some measurement errors, the overall error is small with an average error of 0.102%. The life model can also accurately predict the life of the light source, with a deviation of 8.37% from the actual value. The validation experimental results have shown that the average error between the actual detected light intensity of the light source and the theoretical model is 1.62%, and the error in lifetime evaluation is 10.71%. Therefore, the method is considered reliable for determining the degradation and evaluating the life of the light source. Additionally, in the experiments, the authors found that with aging acceleration by stress, the wavelength and half-height full width of the light source also change, with the wavelength moving towards the long-wavelength direction and the half-height full width increasing. However, no definite mathematical relationship between these changes and degradation was found in this study. Further research in this direction may improve the accuracy of light degradation detection and life assessment.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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