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Original research

LED ring array light source design and uniform illumination properties analysis

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ABSTRACT

For requirements of light source on tiny parts measurement system, this paper puts forward a single wavelength LED to design uniform light of multiple ring. According to detection principle of tiny parts, the design method of ring source is set up, as well as luminescence radiation calculation model of LED ring source. The calculation model of light illumination properties of LED ring array light source are set up and analyzed, light illumination calculation functions of ring source are derived; based on design characteristics of ring source, illumination model and calculation principles of uniform light source are analyzed, the derivation process is established in detail. Through calculation and experimental analysis, illumination uniformity distribution curve of LED ring array light source were given under different detecting plane and the horizontal distance of LED, and the contrast results of illumination uniformity in the *x* axis and *y* axis also were given, the results show that when the distances between detecting plane and LED plane are 80 mm and 100 mm, illumination uniformity of LED ring array light source can reach 0.96.

1. Introduction

With the development of manufacturing industries, detection on tiny parts has become a research in numerous areas, especially high precision measurement on multiple processes and multiple profile parts, it has an influence on development of assembly industry such as aviation, aerospace, weapons [1,2]. To improve manufacturing and size detection of tiny parts, currently, machine visual online detection method is often used, with appropriate background light, and through image capture and processing, related size of tiny parts can be obtained. However, during detection processing on tiny parts, uniform and brightness of background light have an effect on image sharpness of machine visual system, if background light is not uniform or brightness can not meet requirement, then, detection parameters will exist errors [3], in one word, performance of background light will affect the whole system. Usually, background light contains light-emitting diodes (LED), based on properties of tiny parts, it can be square, round or ring source, by unique advantages like luminescence efficiency, compactness, security and stability of LED, it is more and more widely used in the vision field, which needs uniform illumination conditions [4,5]. In tiny parts testing system, uniform illumination and brightness of background light sources will affect the imaging resolution ratio and contrast, high contrast of detecting parts can simplify imaging algorithm, as well as improve the reliability of visual system, therefore, according to detection requirements of tiny parts, studying uniform high contrast of test system is necessary. According to seal parts image detection system, this paper studies array model on LED uniform lighting and luminescence properties of ring source.

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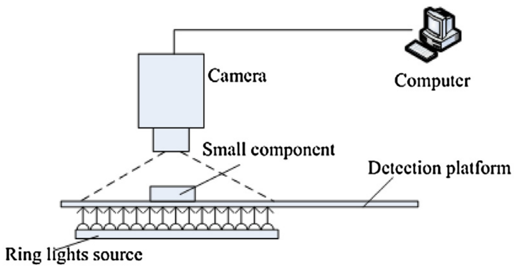


Fig. 1. Basic principle detection of tiny parts.

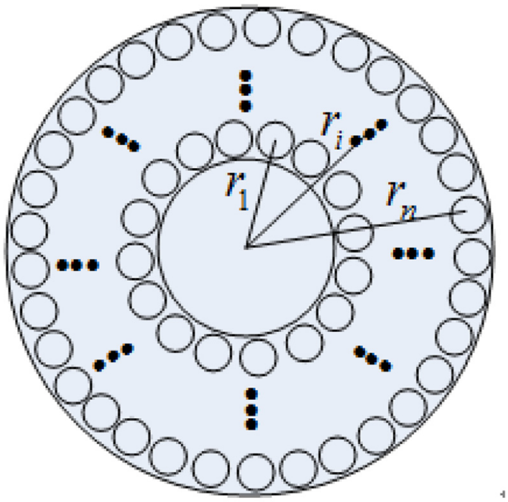


Fig. 2. Ring source.

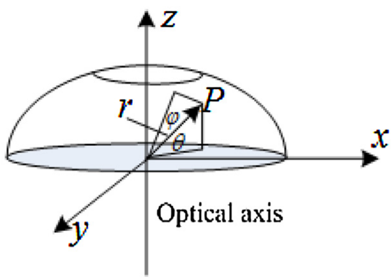


Fig. 3. Diagram of ring LED source placed in the *x*-*y* plane.

2. Array model on LED uniform lighting

2.1. Detection principle of tiny parts and ring source design

Array uniform illumination source consists of multiple light emitting diodes, according to demand, luminescence surface of source can be made ring, linear, square and spherical shape. Tiny parts are mainly round in detection, background light should be ring source to meet detection of round parts, detection principle is shown in Fig. 1, tiny parts are transferred to ring source by belt, through synchronization capture, tiny parts are shoot, size and flaws and other parameters can be obtained by image processing.

From Fig. 1, ring source need to radiate the entire component, the contrast of imaging systems is determined by uniformity and brightness of light source. To get a high-contrast image, LED with 680 nm as its wavelength is used. In Fig. 2, it is a n-ring LED, assume the LED number of every ring is l, radius is r_i, i is the number i LED, $3 \le i \le n$, the number of ring can be chosen according to size of tiny parts. In order to analyze uniformity of ring source, light source distribution model is built for two dimensional direction. In Fig. 3, ring LED source is placed in the x-y plane.

Because the LED is a kind of incoherent light source, illumination in an area is a stack of each one. The radiation distribution on the inner surface of the ring source can be expressed [6,7]:

$$E(x,y,z)=z^m\sum_{i=1}^{n}\sum_{j=1}^{l}\sum_{k=1}^{N}I_j\left\{\left[x-r_i\cos(2\pi k/N)\right]^2+\left[y-r_i\sin(2\pi k/N)\right]^2+z^2\right\}^{-(m+1)/2} \tag{1}$$

Lambert model directional index is m, the number of LED is N. Coordinates of any point $P(x,y,z)$ on the inner surface can be represented by Cartesian coordinate.

$$\begin{cases} x=r_i\sin\theta\cos\varphi \\ x=r_i\sin\theta\sin\varphi \\ z=r_i\cos\theta \end{cases} \tag{2}$$

Calculation method for illumination distribution within ring source surface can be described: center axis of half spherical surface is vertical to the plane of ring array, when luminescence angle $\theta$of LED is determined, the corresponding z can be obtained, by Eq. (1), the corresponding illumination distribution on the half spherical surface can also be get, with changing value of θ, according to integral principle, illumination distribution on the whole half spherical surface can be obtained.

2.2. Illumination model of the LED ring source

In order to build mathematical simulation on the whole ring source, firstly, a single LED illumination model is established. A single luminescence LED can be approximated as a point source, radiation distribution of ideal LED point source is a cosine function, it is expressed as follows [8,9]:

$$E(r_i,\theta)=E(r_i)\cos^m\theta \tag{3}$$

In Eq. (3),$E\left(r_i,\theta\right)$ is irradiance, r_i is the distance between the center of LED and its plane, $\theta$is the angle of any LED light and optical axis. Assume $\theta_{1/2}$ is half attenuation angle, when $\theta=\theta_{1/2}$, $E\left(r_i,\theta\right)=E(r_i)/2$, then:

$$m=\frac{-\ln 2}{\ln\left(\cos\ \theta_{1/2}\right)} \tag{4}$$

When the LED radiate on the plane perpendicular with its axis, there is:

$$E\left(r_i,\theta\right)=\frac{I_{LED}\cos^m\theta}{d^2} \tag{5}$$

In Eq. (5), d is the distance between LED and radiate plane, $I_{LED}$is the light intensity on the normal of LED, then in Eq. (1), the Cartesian coordinate $P(x,y,z)$ can be expressed as:

$$E(x,y,z)=\frac{z^m I_{LED}}{\left[(x-x_o)^2+(y-y_o)^2+z^2\right]^{(m+2)/2}} \tag{6}$$

In Eq. (6), the original coordinate of ring source is (x_o, y_o).

2.3. Performance analysis on uniform light source

As is shown in Fig. 4, it is single LED, target detection plane is illumination plane of every LED in distance T, light exited from ring source is emitted to lens surface, after refraction of incident, and then it approaches the detection plane.

If the absorption and scattering losses are ignored, the ray propagation obeys the law of energy conservation, namely, output luminous flux of light source should be equal to luminous flux of the incident target surface [10]:

$$\iint_{\Omega} I(\theta)d\Omega=\iint_{S} E(x)\cos\ \varphi\, dS \tag{7}$$

In Eq. (7), $I(\theta)$ is the light intensity at the optical axis angle of θ, $E(x)$ is the illumination at T on target surface [11,12], S is emitting curved area, light distribution curve is known as $I(\theta)$, luminous flux of luminescent source is shown in Eq. (8):

$$\Phi=\int_{0}^{\Omega} I(\theta)d\Omega \tag{8}$$

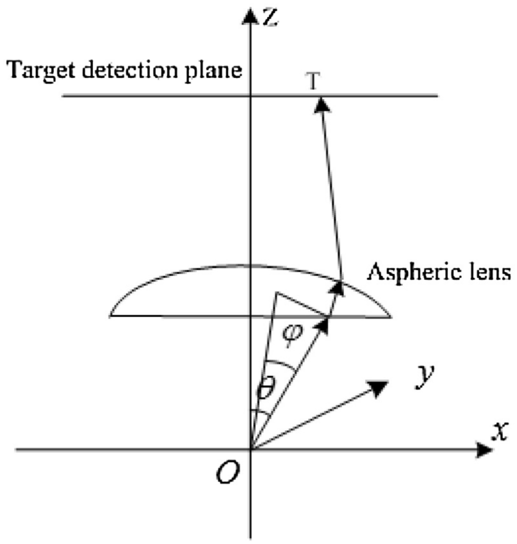


Fig. 4. Designing model of uniform light source.

Conduct integral to luminous flux at any radius, then:

$$\Phi(x) = 2\pi \int_0^x xE(x)\cos\ \varphi\, dx \tag{9}$$

By Eq. (10), all light energy from light source can approach uniform detection surface,

$$\Phi = \int_0^\theta I(\theta)2\pi\ \sin\theta\ \ \cos\ \varphi\, d\theta \tag{10}$$

Assume the average illumination on detection plane is E_0, conduct integral to any (θ, x), then:

$$\Phi = \frac{1}{x^2}\int_0^\theta I(\theta)2\pi\ \ \sin\theta\ \cos\ \varphi\, d\theta \tag{11}$$

When $x = x_{max}$, $\theta = \theta_{max}$, conduct integral to Eq. (12),

$$E_0 = \frac{1}{x_{max}^2}\int_0^{\theta_{max}} I(\theta)2\pi\ \sin\theta\ \cos\ \varphi\, d\theta \tag{12}$$

Then

$$x = \sqrt{\frac{\int_0^\theta I(\theta)\sin\ \theta\ \cos\ \varphi\, d\,\theta}{\int_0^{\theta_{max}} I(\theta)\sin\ \theta\ \cos\ \varphi d\,\theta} x_{max}} \tag{13}$$

According to the law of energy conservation, when curve of light distribution is known, the relationship between emergent angle $\theta$and target plane coordinate x can be obtained.

$$x = \frac{x_{max}}{\sin\theta_{max}}\sin\theta \tag{14}$$

Similarly, the relationship between emergent angle $\theta$and target plane coordinate y can be also obtained.

$$y = \frac{y_{\max}}{\sin\theta_{\max}}\sin\theta \tag{15}$$

According to the coordinate parameters of x and y, as well as illumination functions, function relationship between illumination on the whole detection plane and coordinate of every luminescence point can be obtained.

3. Calculation and testing analysis

3.1. Calculation analysis

In accordance with design principles of the ring source distribution, the ring source on the detection plane is luminous energy synergy of all LED, the irradiance distribution can be expressed as:

$$E_{total} = \frac{\sum\limits_{i=1,j=1}^{n,l} E_{i,j} B\cos\theta \cdot ds}{d^2} \tag{16}$$

In Eq. (16), $E_{i,j}$is the illumination distribution of LED when the coordinate is(i, j), from Eqs. (1) and (6), the illumination distribution of the whole ring source is synergy of all LED. The distance between the inner surface of dome and the light plane is d, B is two-way distribution function [13]. In order to better describe uniformity of diffuse reflection light from the ring source in all directions of space, there is:

$$B = \rho/\pi \tag{17}$$

In Eq. (17), $\rho$is the reflection rate of hemispherical, illumination of light source coordinate is shown:

$$E(x, y, z) = \sum_{i=1}^{n}\sum_{j=1}^{l}\sum_{k=1}^{n+l}\left\{\frac{1}{lu}\cdot P\right\} \tag{18}$$

In Eq. (18),

$$P = \frac{E_{i,j}\rho[P_1 + P_2 + (r_i\cos\theta - z)\cos\theta]}{\pi[(r_i\sin\theta\cos\varphi - x)^2 + (r_i\sin\theta\cos\varphi - y)^2 + (r_i\cos\theta - z)^2]^{3/2}} \quad \text{here,}$$

$$P_1 = (r_i\sin\theta\cos\varphi - x)\sin\theta\cos\varphi$$

$$P_2 = (r_i\sin\theta\cos\varphi - y)\sin\theta\cos\varphi$$

The distance between detection plane and LED is z. Irradiance uniformity is defined as follows.

$$U_{unifomnity} = \frac{E_{\min}(x, y, z)}{E_{\max}(x, y, z)} \tag{19}$$

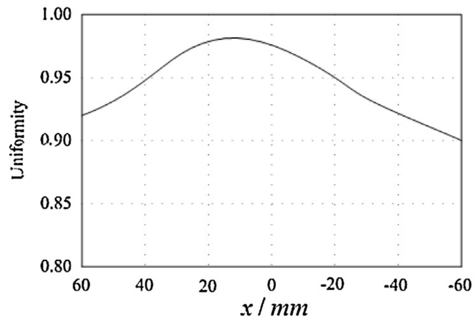
Based on the above analysis, due to detection plane of tiny parts using diffuse glass, assume transmittance of diffuse glass is 0.85, in order to detect uniformity of illumination of ring source, assume the distance between surface of light source and detection plane are 50 mm and 100 mm respectively. The diameter of detection plane is 120 mm. According to designing of ring source and luminous radiation distribution theory [14,15]. When the diameter of detection plane is 120 mm and the distance between surface of light source and detection plane is 50 mm, illumination uniformity is shown in Fig. 5(a) shows the change of illumination in x direction, Fig. 5(b) shows the change of illumination in y direction.

From Fig. 5, illumination on testing plane is symmetrically from the center, the highest value exists in the center, and decreases with the increment of diameter. When the diameter of detection plane is 120 mm and the distance between surface of light source and detection plane is 100 mm, illumination uniformity is shown in Fig. 6. Fig. 6(a) shows the change of illumination in x direction, Fig. 6(b) shows the change of illumination in y direction.

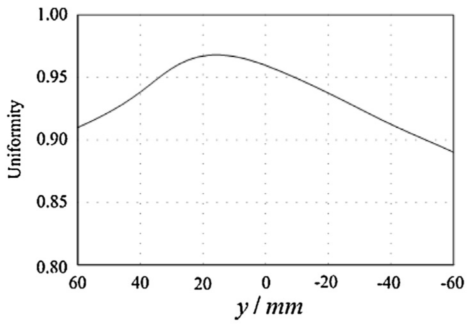
Contrast to Fig. 5, illumination uniformity is essentially the same, however, according to the designing model and analysis theory of uniform light source, when the distance between surface of light source and detection plane are 50 mm and 100 mm respectively, illumination uniformity is slightly different.

3.2. Experimental analysis

In order to make the small parts does not exist shadow, we chose the optimized ring source, the wavelength of LED is 680 nm, the divergence angle is 90°, diameter difference of each ring source is 1.2D (D is diameter of LED, D = 8 mm), the 8 rings of ring source is designed, diameter of ring source is 120 mm. Due to the size of LED is relatively small to the

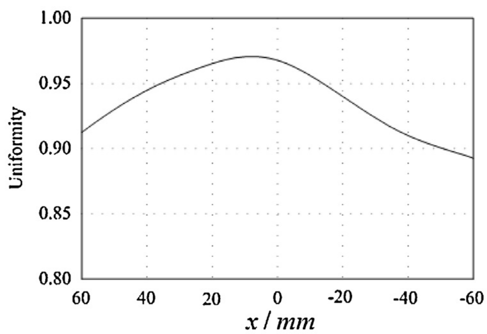


(a)The change of illumination in the *x* direction

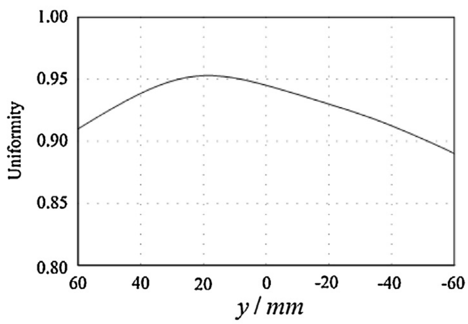


(b) The change of illumination in the *y* direction

Fig. 5. Uniformity of ring source when *z* equal to 50 mm in two dimensional. (a) The change of illumination in the x direction. (b) The change of illumination in the y direction.



(a) The change of illumination in the *x* direction



(b) The change of illumination in the *y* direction

Fig. 6. Uniformity of ring source when z equal to 100 mm in two dimensional.

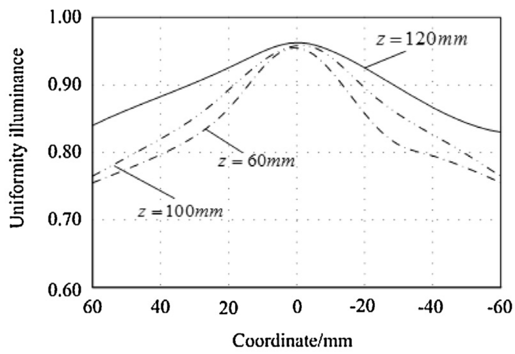


Fig. 7. Uniform illumination changing along with the distance *z*.

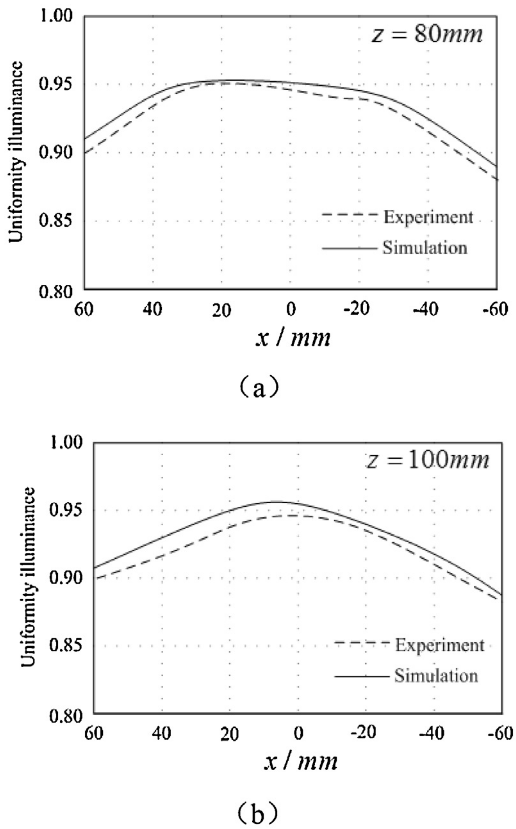
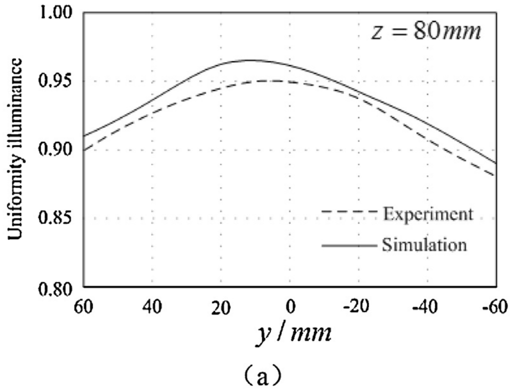


Fig. 8. The distances between detection plane and LED are 80 mm and100 mm along *x* axis.

distance between surface of light source and parts platform, the influence of minor movement to imaging of tiny parts can be ignored, thus, illumination in diffuse window of testing platform is the superposition of each LED. In Fig. 7, it shows the curve of uniform illumination changing along with distance.

According to calculation analysis results of 3.1, measurement range of illumination is a circle with the diameter of 120 mm, TES-1339 is used to conduct illumination measurement. Light meter reads values numerical symmetric interval from center to each side along *x* and *y* axis of detection plane. In Fig. 8(a), when the distance between detection plane and LED is 80 mm, it shows compared results between simulation calculation and the actual measurement uniform degrees, in Fig. 8(b), when the distance between detection plane and LED is 100 mm, it shows compared results between simulation calculation and the actual measurement uniform degrees along the *x* axis; in Fig. 9(a), when the distance between detection plane and LED is 80 mm, it shows compared results between simulation calculation and the actual measurement uniform degrees, in Fig. 9(b), when the distance between detection plane and LED is 100 mm, it shows compared results between simulation calculation and the actual measurement uniform degrees along the *y* axis. From the results in Figs. 8 and 9, the detection measurement



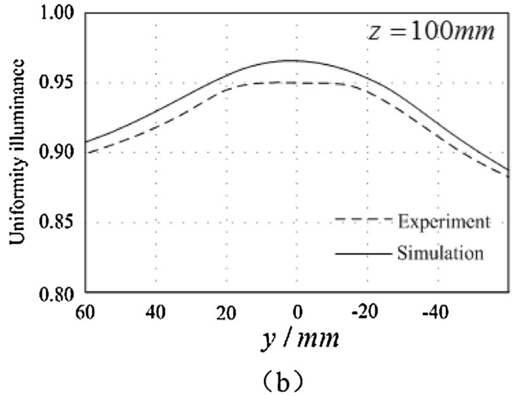


Fig. 9. The distances between detection plane and LED are 80 mm and100 mm along x axis.

is approximate in the direction of x axis and y axis, which indicates the illumination of designed ring source is uniform on testing platform of tiny parts, test results and theoretical calculations are basically the same.

4. Conclusions

Based on detection and test principle of tiny parts, design method and illumination calculation model of ring source are established, as well as the mathematical calculation algorithm, calculation model and characteristic analysis of uniform are set up, from theoretically model, illumination uniform calculation results are obtained from different distances between detection plane and LED plane, through experimental validation, compared results of experimental detection and theoretically calculation are deduced. Finally, the results show the design method of ring source and mathematical calculation algorithm proposed in this paper are rational and scientific. They provide basis for the design of light source in different environmental situations, such as medical lamp, design of planar light source and projection light source, as well as the color light source after mixing multiple LED arrays, the method has a wide application prospect.

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