Quantifying the effect of the Temperature Variable on Optical Anisotropy of Line Spread Function at Image plane

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I- Abstract
It is well known that the variable of temperature degree will effect on the characteristics of any optical component especial lenses and mirrors, because this thermal variable will affect on thermal expansion of the optical component material, we can say (refractive index (n) of the material), Of course this effect will transfer to the ray tracing throw the optical components and which effect on the properties of the spot diagram of image forming. (Even the temperature is increasing or decreasing). When the rays intersect with the image plane, there will be a spot (the spot is intersected between two or more rays that intersect the image plane), the spot distribution will represent the image of the object. This is called a spot diagram. The spot diagram has an important property which are the sizes of spots and type of distribution. So, the thermal effect will appear in these properties of the spot diagram. The main properties of the lens that been affected by thermal is curvature of the surface (R), thickness, object and image planes position (the distances of object & image from the lens center, (S, S') are variables will make changing in the values of focal length of the lens (that means defocus) appear.

Index Terms— Line spread function, Image plane, Temperature variable, Optical anisotropy, Spot diagram.

III- Introduction
During an optical system design, it is important to evaluate all environments that surround the optical system. Such as humidity, mechanical force, thermal effect (temperature variation of the surrounding field), shock-force and so on [3]. Therefore, the design processing in optical systems should take care about all these environments. Especially in operating condition.

The variable of temperature will affect the value of thermal expansion of the material (increasing or decreasing). If the amount of this variable is high (greater than thermal expansion of the lens material), it will affect the geometrical properties of the lens, and its function for image forming. That mean there will be variable in the ray transmission and angle of refraction that will get some distortion and aberrations in the image processing (such as spherical aberration, coma aberration, astigmatism aberration) and the result will be appear on the image plane properties, such as defocus or bad contrast.

The present paper will study the effectiveness of thermal on the spot diagram of the optical system, response to temperature variable and this effect will be on the spot size and way of spot distribution.

IV- Spot diagram and Focal point [4]
Focal point is the best image formed by the optical component and it’s defined as the point which all the refracted rays will collect at the same point on the optical axis at room temperature (Tn Ko), as shown in fig (1). The image will be uniform of spot distribution as shown in the spot diagram fig (2). But if the rays not collected at same point (it will be shifting from focal point, then the result will be defocus, at temperature (Tn X40 Ko) as shown in fig (3), and the spot diagram will be defocus also as shown in fig (4).

Fig (1) Best image at focal point, at room temperature (Tn Ko) (Without thermal effect)
spread function that we can get from the image plane for example (point spread function PSF, line spread function LSF, edge spread function ESF and cumulative line spread function CLSF (or Radial energy distribution RED). In the present paper we used the LSF and CLSF. To find out the efficiency of the optical system through the resulting image it is important to know the spread function which is known generally as a description for the distribution of the intensity in the image plane for any source in the object plane. [9]

Line spread function is a function of intensity distribution at image plane, by using line measurement (in general if the object is a line, then the image distribution will be line spreaded and if the object is point then the image distribution will be point spreaded). We can get LSF by integration with the point spread function (for spot diagram) for one direction, it is Fourier transform of a line through the spot diagram, by consequence, the optical transfer function can only be determined for a single dimension using a single line-spread function (LSF). The type of supposed optical modulator can be defined by using the suitable spot size.[8]

If necessary, the two-dimensional optical transfer function can be determined by repeating the measurement with lines at various angles.

LSF gives us the number of lines (each line represents the number of spots from the spot diagram at image plane) as shown in fig. (5).

Each spot represents the intersection of two rays or more with an image plan.

Its distribution state for object space and image space variables:

$$\delta(y, z, Y, Z)$$

Where \((y, z)\) is point object coordinate and \((Y, Z)\) is spot image coordinate. There for the different between two points is:

$$\delta(y, z, Y, Z) = \delta(Y - y, Z - z)$$

............ (1)

When the object point is on the center of the axis \((y=0, z=0)\) so the gaussian image point will be as a spread function, it is represented as just \(\delta(Y, Z)\).

To get the intensity distribution for spot diagram:

$$I(Y, Z) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} F_o(y, z) \delta(Y - y, Z - z) dy dz$$

............ (2)

**Spread function** [6,7]

Spread function is the distribution of the intensity (spots) in the image plane of any optical system. There are many types of
VI. Effect of temperature degree.

When the temperature increase it will affect directly on the refractive index of the material (depend on thermal expansions) the amount of variable will transfer to the radius of curvature of the optical component (which means shape of it) that makes bending the rays transmitting because the refracted angle will change according to shape variable depending on the snail’s law:

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

where \( n_1 \) and \( n_2 \) are refractive index of incident and refractive mediums respectively, \( \theta_1 \) and \( \theta_2 \) are incident and refracted angles respectively.

The variable of refractive index (n) will affect the shape coefficient (\( q \)) which makes variable in radius of curvature) and position coefficient (\( p \) which affect the distance of object and image). The result of these coefficients will change the spot size and spot distribution fig (4). Therefore, the effect on the spot will transfer to the spot diagram and line spread function as shown in fig (6).

The changing in the value of \( p \) and \( q \) will transfers indirectly on the focal length (f) values, because any changing in (q & p) that mean the temperature was affected on value of refractive index for the lens material (n) and on the material of optical system, there for:

\[ f = \frac{K}{n-1} \]  --------------- (3)

Where K is geometrical constant

That means any variable in the refractive index will be variable in the focal length. That means any variable in temperature (dT) there will be variable in refractive index (dn) [2,4].

Then:

\[ \frac{\partial f}{\partial n} = \frac{K}{(n-1)^2} \]

So, any changing in value of focal length there will be changing in shape focal point (that be defocus or distorted image). The variable in the focal length (\( \Delta f \)), as follow:

\[ \Delta f = \frac{\partial n}{\partial T} \cdot \frac{K}{(n-1)^2} = -\frac{f}{n-1} \cdot \frac{\partial n}{\partial T} \Delta T \]  \[ \text{-------------------------- (4)} \]

There for \[ \frac{\partial f}{\partial T} = \alpha f \]  \[ \text{ troublesome (5)} \]

Where (\( \alpha \)) is Thermal expansion of the lens material

Equation (4) shows if any changing of refractive index value according to the changing of temperature \( (T_a K^0) \) (dn/dT) there will be changing in focal length value

(Also, which means defocus).

Sometimes the holder (The container) of the optical component (such as lens) will also change (the dimension) because of the temperature degree changed. (This change depends on two parameters, (the value of \( \Delta T \) and value of thermal coefficient of the material). The effect of this variable (denoted by \( \delta \)) affects the focal length as well as the lens effect.

So \[ \delta = \alpha f \]  \[ \text{ troublesome (6)} \]

There for the total effective of the system (for lens & holder materials) will (\( \delta_f \))

Which effect on the image forming and equal to: [1,5]: -

\[ \delta_f = \left[ -\frac{f}{n-1} \cdot \frac{\partial n}{\partial T} + \alpha f - \alpha L \right] \Delta T \]  \[ \text{-------------------------- (7)} \]

Where L is the length of the optical system (lens) [along optical axis]

And \( \Delta T = \Delta t \) is equal to:

\[ \Delta t = \frac{L n_1}{c n_2} (n_1 - n_2) \]  \[ \text{ troublesome (8)} \]

Where L is thickness \( n_1 \) is initial refractive index (first medium), \( n_2 \) Final refractive index (second medium).

Fig (6) Line Spread Function at defocus position (With thermal effect, At temperature \( T_a X40K^0 \))

Fig (7) Cumulative Line Spread Function (RED) at focus position (Without thermal effect)
VII- Results & Discussion

From figures (5 and 6) we evaluate the line spread function for both cases, it is clear the peak of LSF for spot diagram fig (2) is higher than LSF of spot diagram fig (4), because the image plane of first one is on focus position while the second is out of focus (defocus), the reason of this different is because of the temperature. By analyses the figures (1,2,5,7 )we note that for normal case (the optical system at room temperature 20°C) and when the object(a point source) be at infinity distance from the lens, the image will be at focal point (also image plane and the spot diagram ) which be as a Gaussian distribution as shown in fig(5 ) of LSF (line spread function) but in fig(6) the LSF will different (lower) because of defocus case, also, the cumulative line spread function CLSF (or radial energy distribution (RED) at image plane for normal case will be as shown in fig (7). But when the temperature changes up to 50°C or more there will be defocus for the image plane which affects the spot diagram, LSF and CLSF as shown in figures (5,6,8).

VIII- Conclusion

1-Any variable of the temperature degree there will be variable in the image forming by the optical component, especially the lenses (because the lens has two curvatures surface), and this variable depending on the thermal expansion of the material for lens and holder(container).

2-The LSF, CLSF (or RED radial Energy Distribution) and Spot diagram are a good Cathedrals that indicate about temperature degree effect on the focal length of the optical system.

3-Any change in the thermal effect will affect on the characteristics of the components of optical system) such as shape (radius of curvature) and position (focal length & image distance) of components.

4-We note that there is not clear effect (or very small amount) of variable temperature degree on the lens between 20-50°C because this range is within the thermal coefficient of the optical components. After and before range of temperature degree there will be effective.