Optically Compensated Zoom Lenses: GA Based Structural Design

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Abstract: A new approach for structural synthesis of optically compensated zoom lenses is reported. An implementation of evolutionary programming facilitates the procedure by carrying out a global search over the available degrees of freedom, namely, powers of the components and the inter-component separations. The efficiency of the proposed method is demonstrated by its convenient amenability in determining thin lens layout of few well known optically compensated zoom lens structures viz Zoomar, Pan-Cinor etc. Illustrative numerical results for other applications are also presented.

1. INTRODUCTION

In a zoom lens system the overall power of the system is varied by moving a group of components, called variator. But the change in the power of the system is always associated with a change in the position of the image plane. The initial position of the image plane can be regained by moving another group of component, called compensator. In an optically compensated zoom lens system, a group of interspaced components are moved with respect to another group of interspaced components of the system. But, the image plane is not strictly fixed; usually, the final image oscillates around the desired image plane as one passes from one extreme of the zoom range to the other. However, by careful design, this shift in image plane can be reduced to a level that is acceptable in many practical applications. Several methods involving Gaussian brackets, continued fractions, and differential equations etc. have been proposed to analyze the Gaussian characteristics of optically compensated zoom lenses [1-13].

Preliminary results of this investigation has been reported earlier[19], that has demonstrated the feasibility of using an algorithm based on evolutionary programming in optimal synthesis of optically compensated zoom lens structures. This report deals with our recent works on improving the search algorithm by extending the domain of the search space.

2. ANALYTICAL FORMULATION

The thin lens structure of a four component zoom lens is shown in Fig.1. In this case, the second and the fourth components are coupled together in such a fashion that the separation between them remains unchanged during any movement of the group. As the overall focal length of a multi-component optical system is decided by the powers of the individual components, and the axial separations between them, the latter are the degrees of freedom available for structural design of a zoom lens. For example, if we consider the four-component optically compensated zoom lens system, the design variables are the powers of the four components, $k_1, k_2, k_3, k_4$, and the inter-component separations $d_1, d_2$ and $d_3$. All these powers are normalized in terms of zoom ratio and the maximum power, i.e. the power of the zoom system in the wide-angle position. Similarly, separations are also normalized in terms of the maximum movement of the coupled components. In the input, generally the normalized power varies from –1 to 0 for a negative component and from 0 to +1 for a positive component. Maximum values of the separations are set to 1 and its minimum values are chosen by experience when the maximum apertures of the lens system changes from one value to the other. Therefore the members of initial population generated by GA consist of a set of normalized powers and normalized separations, but in binary format. So, normalized powers and normalized separations of an arbitrary optical system are obtained by decoding a chromosome. The actual powers and separations are then calculated from their normalized values using following formulae.
\[ k = m \cdot k_{\text{max}} \cdot \bar{k} \]
\[ d = Z_{\text{max}} \cdot \bar{d} \]  

(4)

where \( m \) is required zoom ratio, \( k_{\text{max}} \) is the maximum power in the zoom system, \( \bar{k} \) is the normalized power, \( Z_{\text{max}} \) is the maximum movement that can be allowed in the system and \( \bar{d} \) is the normalized separation. As the input powers are normalized in terms of wide-angle power and zoom ratio, zoom lens having any zoom ratio and wide-angle power can be designed with same input power range. A paraxial ray trace is then carried out through the system to find out the overall power of the system at its initial position. Formulae used for paraxial ray tracing are \(^{[20-21]}\)

\[ u_{n+1} - u_n = h_n \cdot k_n \]
\[ h_{n+1} = h_n - d_n \cdot u_n \]  

(5)

where \( k_n \) is the power of the \( n^{th} \) component, \( u_n \) and \( u_{n+1} \) are the angles of convergence of paraxial marginal ray (PMR) before and after the \( n^{th} \) component respectively, and \( h_n \) is the height of PMR on the \( n^{th} \) component. Therefore, for a zoom lens in air, when \( u_i \) is zero, the focal length of the system can be determined using following relation

\[ f_{\text{eq}} = \frac{h_1}{u_{N+1}} \]  

(6)

where \( N \) is the total number of components in the zoom system. After these initial calculations with the set of powers and separations, randomly selected by GA, two extreme positions of the coupled components are searched to cover the zoom range as much as possible. Bisection search technique is used to locate two extreme positions of the coupled component within the available space for zooming. The overall powers, \( f_{\text{max}} \) and \( f_{\text{min}} \), of the system at these two extreme positions are also determined. So the distance between two extreme positions of the coupled component is required component movement, \( Z \). The shift of the final image plane, \( \Delta \), with respect to a fixed component in the zoom system, is then calculated by setting the lens system at different zoom positions inside two extreme positions of the coupled component.

To facilitate practical synthesis of the structure with the real lenses, \( D_\delta \) of each component is checked at this stage. The required image height \( \eta \) is calculated from required field and power of the system at its wide-angle position using following relation,

\[ \eta = \frac{\tan(\beta_{WA})}{k_{WA}} \]  

(7)

where \( k_{WA} \) is the power of the system at the wide-angle position, and \( \beta_{WA} \) is required field at that position. Incident ray height and field angle at any intermediate zoom position is then calculated using (8) and (9) respectively.

\[ h_1 = \frac{1}{2kF_\delta} \]  

(8)

\[ \beta = \tan^{-1}(\eta k) \]  

(9)

where \( k \) is the power of the zoom system at an arbitrary intermediate zoom position, \( F_\delta \) is required f-number of the system and \( \beta \) is required field angle to maintain image height at the same zoom position. Both paraxial marginal ray (PMR) and paraxial pupil ray (PPR) are then traced again with the help of (8) & (9) and then (5) & (6), at five intermediate zoom positions. Based on the data obtained from ray tracing D-number (\( D_\delta \)) of each component is then calculated using following formula,

\[ D_\delta = \frac{1}{2(h_n + h_{n+1})} \]  

(10)

Where, \( h_n \) is height of the PPR on \( n^{th} \) component. The \( D_\delta \) of each component in the system is then compared with a pre-specified user defined value, and if the \( D_\delta \) for any component becomes higher than the specified value, the algorithm terminates calculation and searches another system.

The merit function (\( \Phi \)) of the system is calculated by using the formula,

\[ \Phi = \omega_1 \times (f_{WA} - f_{\text{max}})^2 + \omega_2 \times (f_{\text{Tel}} - f_{\text{min}})^2 + \omega_3 \times \Delta^2 \]  

(11)

where, \( f_{WA} \) and \( f_{\text{Tel}} \) are required focal lengths of the zoom system at its wide-angle and telephoto positions respectively, \( \omega_1, \omega_2 \) and \( \omega_3 \) are the weighting factors. Correspondingly, a fitness function \( \Psi \) is defined as,

\[ \Psi = \frac{1}{1 + \Phi} \]  

(12)

Target of the optimization process is to increase \( \Psi \) so that \( f_{\text{max}} \) and \( f_{\text{min}} \) gets closer to \( f_{WA} \) and \( f_{\text{Tel}} \) respectively, and the oscillation of the image plane around the reference image position is reduced to as small a value as possible.
After calculation of the fitness function, GA selects the fittest member of the population and stores it separately and goes for the next generation. The other members of the next generation are obtained stochastically.

3. ILLUSTRATIVE RESULTS

Some preliminary results on the use of this algorithm in the design of three different optically compensated zoom lenses are given in Tables 1 to 6. First one is called ‘Zoomar-8’ and manufactured by Zoomar. Table 3 corresponds to a Zoom Lens by manufacturer Research & Development Laboratory called ‘Zoomar’. Table 5 corresponds to a Zoom Lens by manufacturer SOM-Berthiot called ‘Pan-Cinor 100’. These data are taken from reference [22]. In the first example the stop is placed on the 4th component and 1st and 3rd are coupled together. In the last two examples the stop is placed on the 5th component and 2nd and 4th component are coupled together. In the thin lens structure data for all three zoom lenses, power of the components are expressed in mm\(^{-1}\) and separations are expressed in mm.

Table 1: Thin lens data for the zoom lens ‘Zoomar-8’

<table>
<thead>
<tr>
<th>(k)</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-0.018381)</td>
<td>(42.85)</td>
</tr>
<tr>
<td>(0.025734)</td>
<td>(27.85)</td>
</tr>
<tr>
<td>(-0.044115)</td>
<td>(33.57)</td>
</tr>
<tr>
<td>(0.058819)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Image shift \(\Delta\) corresponding to focal length change from \(f_{max}\) to \(f_{min}\) by shift \(Z\) of the coupled components of the zoom system of Table 1.

<table>
<thead>
<tr>
<th>(Z) (mm)</th>
<th>(f_{max}) (mm)</th>
<th>(f_{min}) (mm)</th>
<th>(\Delta) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.50</td>
<td>39.07</td>
<td>13.03</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Table 3: Thin lens data for the zoom lens ‘Zoomar’

<table>
<thead>
<tr>
<th>(k)</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.010397)</td>
<td>(35.67)</td>
</tr>
<tr>
<td>(-0.023305)</td>
<td>(30.39)</td>
</tr>
<tr>
<td>(0.022588)</td>
<td>(2.50)</td>
</tr>
<tr>
<td>(-0.055214)</td>
<td>(23.61)</td>
</tr>
<tr>
<td>(0.062385)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Image shift \(\Delta\) corresponding to focal length change from \(f_{max}\) to \(f_{min}\) by shift \(Z\) of the coupled components of the zoom system of Table 1.

<table>
<thead>
<tr>
<th>(Z) (mm)</th>
<th>(f_{max}) (mm)</th>
<th>(f_{min}) (mm)</th>
<th>(\Delta) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.00</td>
<td>52.97</td>
<td>17.18</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Table 5: Thin lens data for the zoom lens ‘Pan-Cinor 100’

<table>
<thead>
<tr>
<th>(k)</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.004384)</td>
<td>(62.56)</td>
</tr>
<tr>
<td>(-0.003131)</td>
<td>(67.08)</td>
</tr>
<tr>
<td>(0.001879)</td>
<td>(42.20)</td>
</tr>
<tr>
<td>(-0.029432)</td>
<td>(41.07)</td>
</tr>
<tr>
<td>(0.057926)</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Image shift \(\Delta\) corresponding to focal length change from \(f_{max}\) to \(f_{min}\) by shift \(Z\) of the coupled components of the zoom system of Table 3.

<table>
<thead>
<tr>
<th>(Z) (mm)</th>
<th>(f_{max}) (mm)</th>
<th>(f_{min}) (mm)</th>
<th>(\Delta) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.75</td>
<td>100.00</td>
<td>25.14</td>
<td>0.95</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

Further work is in progress and will be reported later.

REFERENCE