Design and Development of Optimum Structures for Multi-component Zoom Lenses using Prophylactic Strategy- An Overview

Design and Development of Multi-component Zoom lenses

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Abstract— Based upon the prophylactic strategy for optical design developed in Department of Applied Optics & Photonics, University of Calcutta, this paper reports an overview of the design of multi-component zoom lens. This strategy includes the effective use of the thin lens aberration theory and paraxial ray optics in reducing a formidable design problem with large degrees of freedom into a set of sub-problems with considerably lower degrees of freedom. Some of the design steps involve global or quasi-global optimization of design variables, and others are facilitated by computer implementation of analytical methods. The total primary aberrations of the whole system in selected zoom positions are kept within a given targeted value. Illustrative numerical results of the design procedure are presented.

Keywords-Optical design, lens design, global optimization, structural design, computer aided lens design, multicomponent lens systems synthesis and evolutionary programming, aberration correction.

I. Introduction

A varifocal lens is one in which the focal length of the lens can be continuously varied over a range. In such a system, the image position generally moves with a change in focal length; but if some arrangement, optical or mechanical, is provided by which the image plane can be held fixed for all practical purposes, then the system becomes a zoom lens [1]. In general, a zoom lens is a multi-component lens system where the magnification of the image of a fixed or moving object can be varied continuously by axial movement of two or more components. Axial movements of more than one component produce a change in the equivalent focal length of the system, while keeping the axial location of the resultant image plane unchanged. [2-4]. The ratio of the maximum focal length to the minimum is called the zoom ratio, while the zoom range refers to the range of focal lengths available. The component of a zoom lens that is used to vary the focal length is often called the variator, while some other component that is shifted axially to maintain a fixed image position is known as compensator.

II. A Brief History of Zoom Lens Design

A. *Early Research Works – a brief glimpse*

Early approach to a varifocal lens system made use of a Telephoto lens consisting of two separated lens components of e.g., opposite power. The separation between the two components could be charged by a rack and pinion motions in such a way as to keep the image automatically in focus while the focal lens was being varied. A significant development in zoom lenses was the introduction of the zoomar lens for 16 mm cameras by F.G. Back in 1946 [5-7]. The adoption of zoom lenses for motion picture cameras developed slowly, the television industry

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immediately realized the advantages of this new lens. The monograph on zoom lenses published by Clark [2] in 1973 is a documentation of the development of zoom lenses till the end of 1960s. In the 1970s, Betensky [8-21] of Open Associates, and in the 1980s, Tanaka [22-35] of Cannon worked extensively on improving quality of zoom lenses. Betensky worked on aberrational characteristics and many other aspects of zoom lenses. Tanaka primarily dealt with the paraxial characteristics of mechanically compensated zoom lenses, using Gaussian brackets [29].

During the last two decades, many new possibilities are being explored to produce small, light weight, easy to use and simultaneously, cost effective zoom lenses. Zoom lens system with radial gradient index (GRIN) lens has been reported for this purpose by Tsuchida et al [36] in 1992. In case of zoom lenses with symmetrical power arrangement, it is possible to replace each lens group by a single GRIN lens element. So, use of GRIN lenses reduces both the system length and the weight of the system. In another approach, refractive lens components are being replaced by the light weight diffractive optical elements (DOE) [37-40]. In the last century, no means for changing the power of an individual lens element in situ was available. Thus the focal length of the overall system could only be changed by shifting individual components along the optical axis.

Invention of spatial-light-modulators (SLM) and liquid lenses in recent past, and advances in technology have provided a novel way for changing powers of individual components. It is becoming possible to alter the focal length of a multi-component system by changing powers of individual components, keeping their separations fixed. This has reduced the overall length of zoom lenses noticeably. Zoom lenses with such active components [41, 42] have recently been explored by Wick and Martinez [43], De-Ying Zhang et al [44], Sung-Chan Park and Jun Park [45], and Miks and Novak [46]. Over the years, the distinct roles of four different groups of lenses, namely, the focusing group, the variator group, the compensator group and fixed follow-up group are giving ways to lesser number of groups combining functions of some of the groups for obtaining light and compact zoom lenses. For example, Tanaka in 2010 [47] of Fujinon Corporation reported a zoom lens system that uses the same lens group for both focusing and image compensation during zooming, instead of using two separate lens groups for the purpose. This zoom lens also provides image stabilization against image plane vibration by moving a lens element almost orthogonally to the optical axis. Furthermore, use of CCDs, which is more sensitive than a photographic film, reduced the amount of light energy required, and consequently the demand for small F-number of lenses, for faithful recording of the image. This has facilitated the use of short focal length lenses as individual components of the zoom system, and has helped to achieve larger zoom range with a smaller system length.

B. Classification of zoom lenses

Depending upon the movements of the lens components of a zoom lens, they can be broadly classified in three types, namely mechanically compensated zoom lenses, linearly compensated zoom lenses, and optically compensated zoom lenses. In a mechanically compensated zoom lens, a lens component, called the variator, is moved axially to change focal length of the zoom lens. The concomitant axial displacement of the final image plane is compensated by moving another component, called the compensator, along the optical axis. In a linearly compensated zoom lens, alternating lens components are moved axially, maintaining a linear relationship among them. Over the zooming range, the final image plane swings axially, with small magnitude, around the desired image plane. An optically compensated zoom lens is practically a special case of linearly compensated zoom lens where alternating components are coupled together, and moved axially to vary magnification of the image. This added restriction imposed on component movement increases the magnitude of oscillation of the final image plane. In practice, shifts of image plane over the zooming range can be tolerated so long as they are within the tolerable depth of field of the imaging system. In some applications, somewhat larger axial shifts are admissible, as they have provisions for refocusing for the whole system. The problem of structural design of a zoom lens involves determination of

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powers of individual components and movements of the moving lens components to achieve desired goals as per the type of lens.

III. THE DESIGN PHILOSOPHY

The process of designing a multi-component zoom lens system requires a considerable amount of numerical calculation. Two distinct philosophies are evident. “The first philosophy suggests the establishment of a universal merit function and the development of a closed procedure for minimizing its value without violating physical constraints. The second philosophy suggests the development of a flexible procedure which allows the designer to exercise individual control over a number of image characteristics. The characteristics should be easily calculable since several sequences of iterations may be performed as the designer changes his estimates of the relative importance of various characteristics” [48]. Although debate on the two philosophies continues, the second one is more popular than the first among the lens designers.

A. A Prophylactic strategy towards global sysnthesis

The problem of lens design can be formulated mathematically as a problem of constrained optimization of a multi-objective function in the multivariate hyperspace formed by available degrees of freedom. In general, no analytical solution of this problem is available, except for trivial cases. The designers have had to take recourse to numerical or semi-analytical procedures for tackling this problem. In order to reduce the role of heuristics and wild empiricism in the design of conventional lens system and to develop a systematic procedure for tackling the problem of design of unconventional optics, a prophylactic strategy for ab initio synthesis of lens system is being worked out [48].

This strategy makes an effective use of the thin lens aberration theory and paraxial analysis in reducing a formidable design problem with large degrees of freedom into a set of sub-problems, each with considerably lower number of degrees of freedom. The strategy broadly involves two steps, namely :

STEP I : Generation of a set of globally or quasi-globally optimum starting points for a specific design.

STEP II : Evolutionary optimization of the Starting Designs.

The basic Flow chart pertaining to this strategy requires seven stages. Stage I involves determination of one or more thin lens structural layouts to be worked out by analytical techniques to satisfy paraxial requirements and desired Petzval curvatures, if any, of the multicomponent lens system [52]. Stage II involves determination of Optimum Central Aberration requirements for each individual component to satisfy aberrational requirements for the overall system. Stage III is related to the determination of optimum thin lens structure for each component for satisfying its individual paraxial and central aberration requirements from a set of preferred optical glasses. Stage II and III makes use of global optimization procedures in practical implementation. Stage IV involves the appropriate thickening of thin components of the candidate thin lens layouts using analytical techniques with a minimal change in Gaussian and aberrational characteristics of the overall system. The analytical method used in this stage is the local optimization techniques, namely the damped least squares etc. In the final stage, in stage V, the re-optimization of the thick lens system is based done based upon considerations like cost, weight, ease of manufacture, ergonomics, opto-mechanical compatibility etc.

B. Illustrative Results

In this paper we have used the prophylactic strategy to design a five component 3X optically compensated zoom lens. The specifications of the required zoom lens are as follows :

- Zoom type : Optically compensated Zoom lens
- Focal length range : 100 mm – 300 mm.
- Stop Position : On the first surface
- Semi-field : 7.5 Degrees
- Glass : Two types of radiation resistant glasses are used specifications are given below :

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Name	R.I.	V-No.	Dispersion
Glass – 1	1.51996	63.03	0.008249
Glass – 2	1.62128	36.61	0.01697

- Operating Wavelength : 0.5876 µm
- Wavelength Range : 0.4861-0.6563 µm

C. Individual Stages for designing an Optimal thin lens structure

A five component zoom lens system is judiciously chosen which covers the focal length range of 100 mm – 300 mm. The second and fourth components are coupled together and are moved simultaneously during zooming. Powers of individual components and their inter-component separations, at wide angle position are given. Optical Invariant, the initial ray height and their angles of incidence are also given. The quasiglobal optimal thin lens structure use five component optically compensated zoom lens structure is shown in fig. 1.

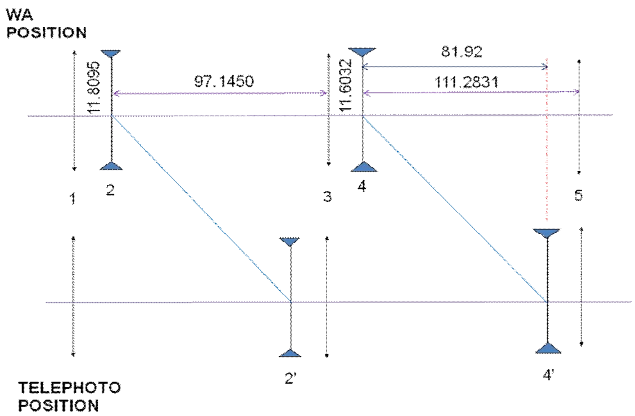

Fig.1 Optimal thin lens structure of Five Component Optically Compensated Zoom Lens

From the figure it appears that out of five components 1st, 3rd and 5th components are fixed while the 2nd and 4th components are moving couples and the coupled components are moved 81.92 mm along the axis to cover the whole zoom range.

Optimal thin lens structures like a singlet, cemented doublet, broken contact doublet or a triplet is searched for five components of the zoom lens structure. In this stage the shape factors of the lens element and dispersion are determined. These two factors collectively determine the curvatures of the final lens elements. Shape factor X of a single lens element of spherical interfaces with curvatures C_1 and C_2 is given by, $X = \dfrac{C_1 + C_2}{C_1 - C_2}$.

Power K of the lens element of refractive index µ is given by, $K = (\mu - 1)(C_1 - C_2)$.

Hence, the dispersion of a component is calculated using the formula, $D = \dfrac{\mu - 1}{V_{NO.}}$.

The curvatures of the 1st and 2nd surfaces of any refracting element are determined by : $C_1 = \dfrac{1}{2}.(\dfrac{X_2 + 1}{\mu - 1}).K_1$ and $C_2 = \dfrac{1}{2}.(\dfrac{X_2 - 1}{\mu - 1}).K_2$, where X_1 and X_2 are corresponding shape factors respectively.

D. Exact values calculated for Five component optically compensated zoom lens

The Gaussian layout of the components have been carried out with the different terms with total no. of components (N) =5 where K_m is the power of the m-th component,with X_m is its Shape factor and C_m is the curvature. Separations between the individual component d_i with ρ_m as semi-aperture.

1. FIRST COMPONENT : A Broken Contact Doublet

TABLE - 1

ρm	K1	X1	Mat-1	K2	X2	Mat-2
10	-0.00305	-4.98657	Glass 2 µ2=1.62128 V2=36.61 D2=0.01697	0.0065	-0.10560	Glass 1 µ1=1.51996 V1=63.03 D1=0.008249

where $d_i = 0, \forall i$

TABLE - 2

C1	C2	C3	C4
0.009785	0.014695	0.00559	-0.00691

2. SECOND COMPONENT : A Broken Contact Doublet

TABLE - 3

ρm	K1	X1	Mat-1	K2	X2	Mat-2
15	-0.02113	-0.47552	Glass 1 µ1=1.51996 V1=63.03 D1=0.008249	0.01121	2.28238	Glass 2 µ2=1.62128 V2=36.61 D2=0.01697

where $d_i = 0, \forall i$

TABLE - 4

C5	C6	C7	C8
-0.01066	0.029981	0.029613	0.011569

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3. THIRD COMPONENT : A Broken Contact Doublet

TABLE - 5

pm	K1	X1	Mat-1	K2	X2	Mat-2
10	-0.00808	-2.07362	Glass 2 μ2=1.62128 V2=36.61 D2=0.01697	0.01519	0.35832	Glass 1 μ1=1.51996 V1=63.03 D1=0.008249

where $d_i = 0, \forall i$

TABLE - 6

C9	C10	C11	C12
0.006981	0.019987	0.019841	-0.00937

4. FOURTH COMPONENT : A Broken Contact Doublet

TABLE - 7

pm	K1	X1	Mat-1	K2	X2	Mat-2
25	0.00437	-3.28714	Glass 2 μ2=1.62128 V2=36.61 D2=0.01697	-0.00898	0.64522	Glass 1 μ1=1.51996 V1=63.03 D1=0.008249

where $d_i = 0, \forall i$

TABLE - 8

C13	C14	C15	C16
-0.00804	-0.01508	-0.01421	0.003064

5. FIFTH COMPONENT : A Broken Contact Doublet

TABLE - 9

pm	K1	X1	Mat-1	K2	X2	Mat-2
25	0.01415	-0.41570	Glass 1 μ1=1.51996 V1=63.03 D1=0.008249	-0.00716	2.36906	Glass 2 μ2=1.62128 V2=36.61 D2=0.01697

where $d_i = 0, \forall i$

TABLE - 10

C17	C18	C19	C20
0.00795	-0.01926	-0.01941	-0.00789

Each of the five components are realized by using broken contact doublets due to the reason that none of them could be realized with a singlet of spherical interfaces and the broken contact doublets are preferred in comparison with a cemented doublet in order

Determination of central aberrations

In designing a zoom lens, the principal problem is to maintain good aberration correction over the zoom range. The central aberrations of each of the five components are determined. The central aberration of any component is defined as the value of the aberration when stop is placed over the component. The aberration of the complete system can be determined using stop shift formulae as given below [49, 50] :

$$\sum S_1 = \sum_{m=1}^{M} (S_1)_m \text{....(1)}$$

$$\sum S_{II} = \sum_{m=1}^{M} (S_{IIC})_m + \sum_{m=1}^{M} \left(\frac{\bar{h}_m}{h_m}\right)(S_1)_m \text{....(2)}$$

$$\sum S_{III} = H^2 \sum_{m=1}^{M} k_m + 2\sum_{m=1}^{M} \left(\frac{\bar{h}_m}{h_m}\right)(S_{IIC})_m + \sum_{m=1}^{M} \left(\frac{\bar{h}_m}{h_m}\right)^2 (S_1)_m \text{....(3)}$$

$$\sum S_V = (3+p)H^2 \sum_{m=1}^{M} \left(\frac{\bar{h}_m}{h_m}\right)k_m + 3\sum_{m=1}^{M} \left(\frac{\bar{h}_m}{h_m}\right)^2 (S_{IIC})_m + \sum_{m=1}^{M} \left(\frac{\bar{h}_m}{h_m}\right)^3 (S_1)_m \text{....(4)}$$

$$\sum C_L = \sum_{m=1}^{M} (C_L)_m \text{...(5)}$$

$$\sum C_T = \sum_{m=1}^{M} \left(\frac{\bar{h}_m}{h_m}\right)(C_L)_m \text{...(6)}$$

where $\sum S_1, \sum S_{II}, \sum S_{III}, \sum S_V, \sum C_L \;\&\; \sum C_T$ are spherical aberration, coma, astigmatism, distortion, longitudinal and transverse chromatic aberrations respectively of the overall system. H is the Lagrange Invariant of the system, h_m and $\bar{h}_m$ are the heights of the Paraxial Marginal Ray (PMR) and Paraxial Pupil Ray (PPR) respectively at the m^{th} component. M is the total number of components and p is constant having value of 0.63. Curvature of an optical system denoted by $\sum S_{IV}$, depends on the power of the individual components and cannot be manipulated by any stop shift, i.e., $\sum S_{IV} = p\sum_{m=1}^{M} k_m$.

From expression (1) it is apparent that stop shift does not affect the spherical aberration and longitudinal chromatic aberration of the system. The value of other aberrations after any stop shift

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depends on the spherical aberration, central coma, and longitudinal chromatic aberrations of individual components. It is significant to note that to obtain an aberration free overall system, it is mandatory to use aberrated components and not an aberration free component and at the same time, the required aberrations of the components are not arbitrary. Instead, they should remain within some target values.

IV. CONCLUDING REMARKS

For stable aberration correction in zoom systems, central aberrations of each component should be such that the overall aberrations of the zoom system do not change much over the zooming range. Stop shift formula and conjugate shift formula of primary aberration theory provide the basis for development of analytical approach to tackle the problem. The complexities involved in implementing the two shift operations in cascade, on commutability of the operations should be taken into consideration.

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