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An Aspheric Grin Ray Trace Program For Thermal Analysis of Optical Systems

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Abstract

In this communication we describe a program which can ray trace through systems bounded by spherical/aspheric surfaces together with the option to trace through media having graded index profile (GRIN) for one or more components. This program is useful for analysing the performance of lenses subjected to thermal gradients.

Key words: Grin, lens design, optical systems

Introduction

Effect of temperature changes on the performance of optical systems have assumed great importance, especially for military and space borne equipment. It is of importance if predictions can be made about the performance of these systems insitu or the performance deterioration can be predicted with certainty in these cases.

A uniform increase in temperature causes an increase in the radii of curvature, element thickness, refractive indices of optical components and a change in air spaces caused by the expansion of the mount material. Even the refractive index of the surrounding medium, normally air, undergoes a change. The uniform change in temperature manifests itself as a defocussing error, however, its effect on the aberrations of the systems is less by an order of magnitude.

Thermal Gradients

A simplistic approach is to consider a single lens as illustrated, in Fig.1. The central thickness of the lens is T_0 and the thickness at a point P where an axial ray passes through the lens is T. A radial temperature gradient does not affect the temperature at the axis of the lens. Thus the central temperature and hence the central thickness T_0 remains constant. In contrast the thickness T at the point P increases to $T + dT$ because of a temperature change dt. The change in optical path between the plane AA' and BB' as a result of the temperature gradient is given by the relationship

$$(n - n_{air}) * (T_0 - T) - nT_0 + (n + dn) * (T_0 - T - dT)$$

which is approximately equal to

$$T_0\{(n - n_{air}) * X_g dt + dn\}$$

It is apparent that the change is dependent only on the lens thickness. However the transverse ray aberrations resulting from this optical path difference will depend upon the lens diameter and focal length. The magnitude of this effect can be estimated by substituting appropriate numerical values. This effect can be quite pronounced in highly corrected systems.

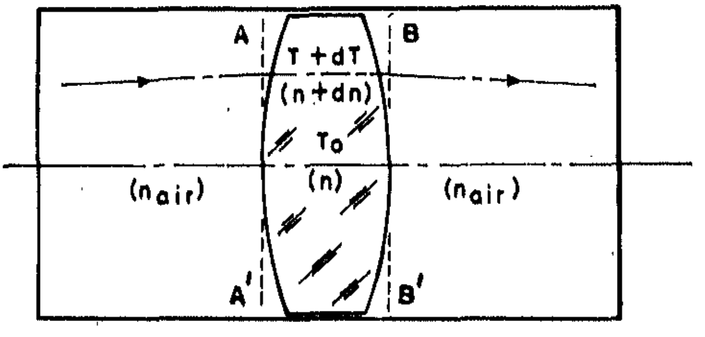

Figure 1. Radial thermal gradient in a simple lens

A rigorous analysis of the radial thermal gradient can be done in the following way:

Thermal gradients in optical systems occur in transient situations such as changing temperature environment. It is rather difficult to calculate the effect of these changes, except in some specialised cases where some simplifying assumptions are made.

1. One such assumption is that the temperature profile is radially symmetric. This situation is quite logical for a typical component mounted in a cylindrical fashion. In this kind of situation the heat transfer from the environment or vice-versa is going to take place through the rim of the component which is in contact with the mechanical mount.

2. Another assumption that has to be made is regarding the distribution of the temperature from center to the periphery of the component. Based on the experiments conducted on optical disks, it can be assumed that the temperature distribution varies as the square of the

radial distance from the optical axis or as is commonly known, the distribution is parabolic in nature.

Under these simplifying assumptions it is possible to consider the system for, mathematical analysis.

1. We can now consider the zonal variation in the thickness of the lens to manifest itself as a change in the spherical profile of the component converting it into a general aspheric.

2. On the other hand the refractive index changes occurring as a result of temperature change can be considered to generate a GRIN profile which can be determined by curve fitting the thermal profile calculated above.

Thus if we want to evaluate the system we have to have a ray trace procedure which can take care of refraction across an aspheric boundary separating the two media as well as to transfer the ray coordinates inside a GRIN media. Hence we need an Aspheric GRIN Ray Trace program to do the analysis. Welford scheme of ray tracing is internationally accepted, which can be further extended to include the case of aspheric surfaces. The only difference between the two is the iterative evaluation of the point of intersection of the ray with the surface in the latter case. The GRIN ray tracing is based on the well known Ray Path equation:

$$\frac{d}{ds} \mid n.\frac{dr}{ds} \mid = \nabla n \tag{1}$$

where

r is the position vector of the ray (x,y,z)

n is the refractive index of medium

s the independent variable & it is the Ray Path

ds is an element of arc length along the ray

A new variable t is defined as follows

$$t = \int \frac{ds}{n}; \quad dt = \frac{ds}{n} \tag{2}$$

and with this simplifying assumption, equation (1) reduces to a convenient form

$$\frac{d^2 r}{dt^2} = n\nabla n; \quad \frac{d^2 r}{dt^2} = \frac{1}{2}\nabla n^2 \tag{3}$$

Depending on whether the refractive index profile is defined in terms of $n(r)$or $n^2(r)$, one of the above equations can be used. By further defining an Optical Ray vector T where

$$T = \frac{dr}{dt} \tag{4}$$

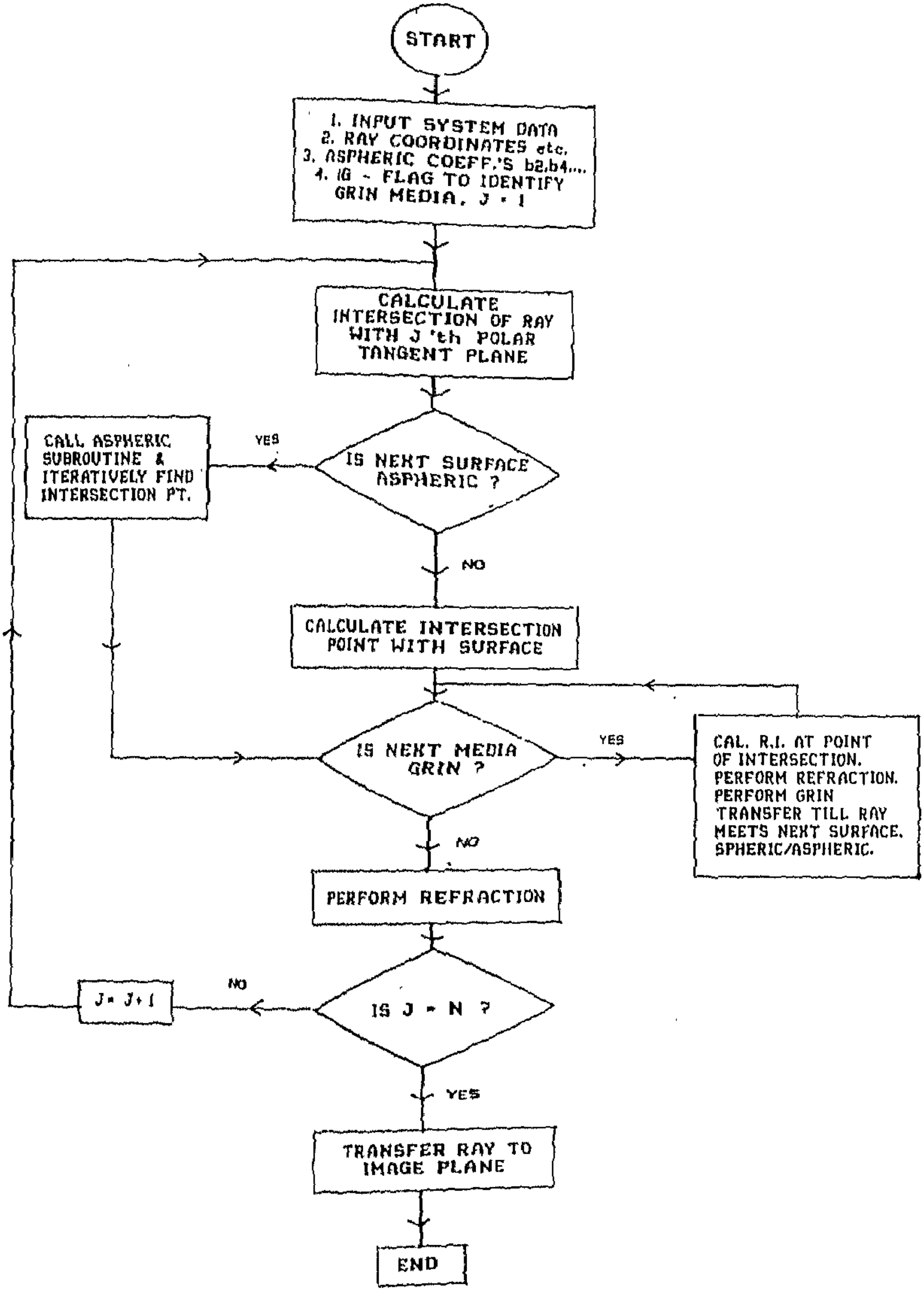

Figure 2. Flow chart of the ray trace program

The components of the vector become the three optical direction cosines

$$T \equiv \frac{dr}{dt} \equiv n\frac{dr}{ds} \equiv in\frac{dx}{ds} + jn\frac{dy}{ds} + kn\frac{dz}{ds}$$

$$T \equiv in \;\; Cos\alpha + jn \;\; Cos\beta + kn \;\; Cos\gamma \tag{5}$$

where α, β, γ are the angles that the ray direction makes with the x,y,z axes respectively.

Since in most of the cases of practical interest the index is isotropic ∇n^2 does not depend on the Optical Ray Vector or dr/dt and one can make use of the shortened version of the Runge-Kutta method to evaluate the first differential equation. This method has been shown to be very accurate inspite of the large step widths of Δt. We have used this scheme for the evaluation of ray tracing through the GRIN media. We have made suitable changes in the coordinate system to make it compatible with the Welford scheme. Another modification has been made in finding the point of intersection with the next surface. Here we have used an iterative evaluation in preference to the method described by (Sharma & Ghatak 1987) as this was found to converge much faster without any loss in accuracy. This scheme also enables us to evaluate the Optical Path Length (OPL) through the GRIN media, which in combination with suitable changes in Welford scheme can be used to evaluate the total OPL through the entire system.

It was our endeavour to write down a ray trace program which can trace through normal systems comprising of homogeneous refractive index media bounded by spherical or aspheric surfaces as well as the one which can ray trace through a GRIN component bounded by spherical or aspheric surfaces. The algorithm of the scheme can be best understood through the flowchart given in Fig.2.

Program Description

The system data is fed into the program. This includes aspheric coefficients, if the system incorporates one or more aspheric surfaces. It also enquires whether any intermediate medium from object to image space is GRIN and in case the answer is 'yes' requires to be fed the values of GRIN coefficients in each case. Program then asks for the ray trace data. As per the Welford scheme, one first obtains the intersection of the ray with the polar tangent plane. The program checks whether the next surface is spherical or aspheric. If it is spherical, it proceeds with the normal Welford scheme and finds the point of intersection with the surface. In case the surface is aspheric, it iteratively locates the point of intersection. Once the intersection point is located the program checks whether the next medium is normal or GRIN. In case the next medium is GRIN then the program calculates the refractive index of the medium at the point of intersection. Once the refractive index is known the refraction is performed in the normal way. After the refraction is performed the ray has to be transferred to the next surface. There are two options again. In case the medium is isotropic the transfer of the ray proceeds in the normal way. Otherwise the ray path has to be integrated inside the medium with small steps of Δt if thickness given. After the ray is transferred across each step Δt, it must be ensured whether or not the ray has crossed the next surface i.e., into the next media. For that the z-coordinate of the ray is checked. If it exceeds the value of the central thickness of the lens less the sag of the next surface at the corresponding height, the

Δt step is halved and ray trace repeated from the previous step. This process is

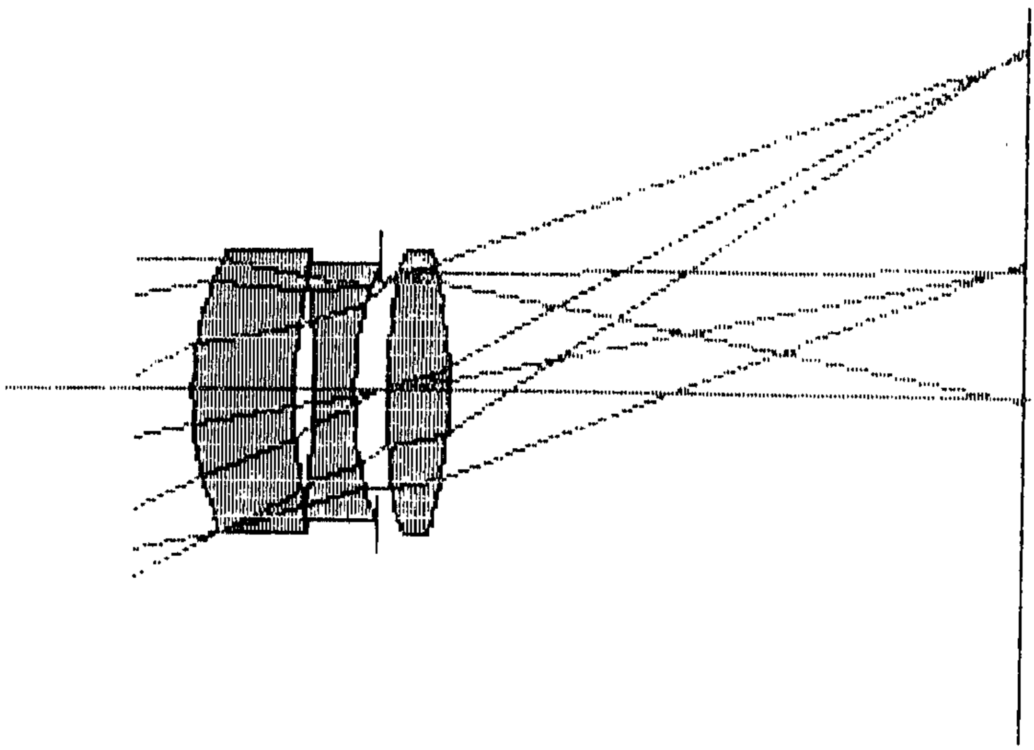

Figure 3. Optical Ray path through Normal & Grin Glass

EFL = 11.6753
grintrip

RADIUS	SEPN	CLR DIAM	MATERIAL
4.801	1.780	4.46	LASF30
10.929	0.294	4.46	Air
-15.060	0.733	4.00	SFN64
5.171	0.444	4.00	Air
PLANE	0.100	3.37	Air
12.610	1.021	3.60	LAFN21
-8.460	9.197	4.40	Air
PLANE		12.15	

repeated to find the exact intersection point at the next surface. The same procedure is followed at each subsequent surface.

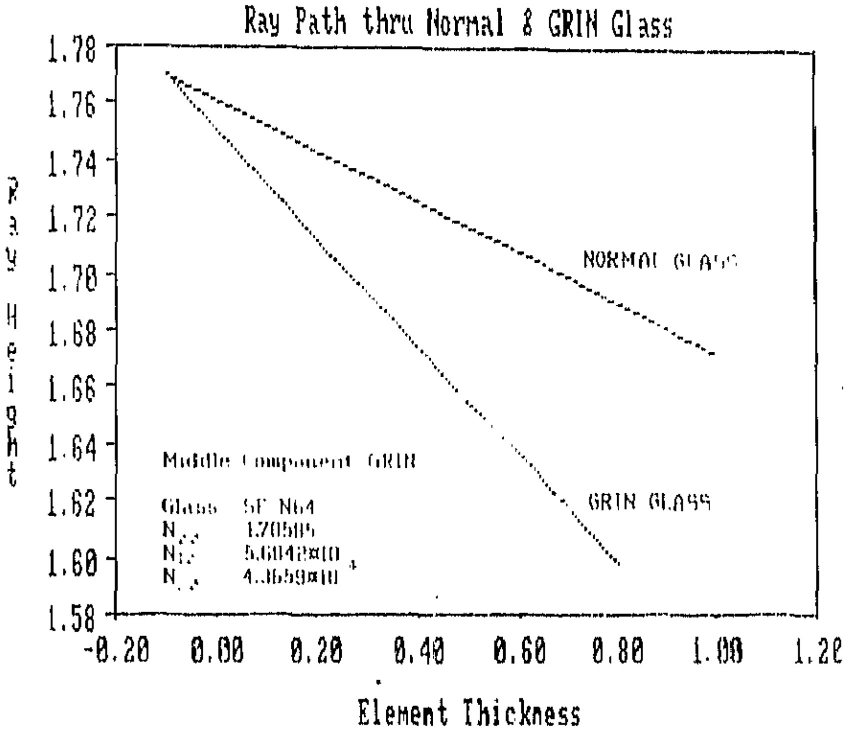

Figure 4. Ray path through Normal & Grin Glass

The program results have been verified with the help of the example of a GRIN singlet mentioned in Moore (1975). In order to demonstrate the working of the program we have considered a triplet with central negative component made of GRIN material *e.g.* GT 1, (Caldwell & Moore 1986). The ray traced through the system has the following specifications at the first polar tangent plane of the system:

$$x = 0.0 \quad y = 2.08405 \quad z = 0.0 \quad (optical \;\; axis)$$

$$l = 0.0 \quad m = 0.0 \quad n = 1.0$$

The effect of the GRIN glass has been brought out in Fig.4 where the ray path through the middle component has been plotted. The height of the ray at the first surface of the middle negative component is 1.770521. If we neglect the GRIN coefficients and treat the glass as normal (isotropic), the emergent ray height works out to be 1.671161. However, if the GRIN coefficients are taken into account the ray height becomes 1.59928. Thus we have demonstrated that our program works for systems comprising of normal and GRIN components.

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