Analysis of Method for Determination of Parameters of Cemented Doublet

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This work presents a noninvasive method of determination of internal parameters of an optical system of a classical cemented doublet. Parameters are calculated from noncontact measurements without any damage or dismantling of the doublet.

1 Introduction

A cemented doublet is a frequently used optical element in the design of various optical systems, which is composed of two lenses cemented together where the second radius of curvature of the first lens and the first radius of curvature of the second lens is identical.

In practice it is often needed to analyze the unknown geometrical and optical parameters of the cemented doublet in a non-destructive way without a separation of individual lenses of the doublet. Imaging properties and paraxial optical parameters of the doublet depend on the mentioned design parameters. It is possible to measure external parameters relatively easily by various measurement techniques.

However, the internal parameters cannot be measured directly. In case refractive indices of lens materials are known one can easily calculate the remaining unknown from measured external parameters and measured paraxial optical properties. In case the refractive indices of lens materials are unknown, then it is not so easy to determine precisely the internal parameters of the doublet.

We propose and analyze an experimental method for the determination of internal parameters of the doublet on a basis of measurement external geometric parameters of the doublet and paraxial properties and aberrations of the doublet. We describe a procedure for the calculation of unknown parameters of the doublet from experimentally measured geometrical and optical parameters of the doublet using an optimization method. The method calculates unknown parameters in such a way that it corresponds to experimentally measured parameters of the doublet. The proposed method and analysis can be also used for the determination of parameters of fluidic lenses with a variable focal length.

2 Parameters of cemented doublet

A cemented doublet (Fig.1) has seven design parameters, namely three radii of curvature (r_1, r_2, r_3), two values of central thickness (d_1, d_2) and two values of refractive index (n_1, n_2) of individual lenses, from which the doublet is composed. Figure 1 presents an optical scheme of a cemented doublet, where F and F' denotes object and image focal point of the doublet, n_0 and n_3 are refractive indices of object and image media and the meaning of other symbols is clear from Fig.1.

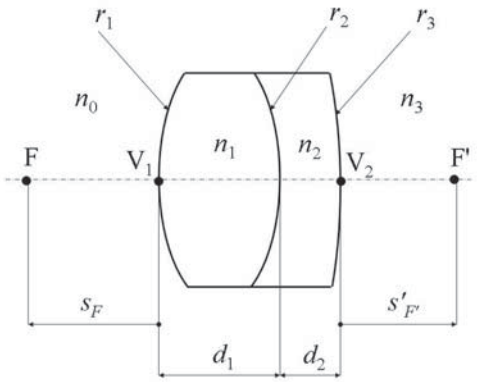

Fig. 1 *Optical scheme of a cemented doublet.*

3 Method of determination of internal parameters of cemented doublet

Consider that we are able to measure radii of curvature r_1 and r_3, the overall central thickness d, the focal distance f', the position of image focal point $s'_{F'}$ and refractive indices (n_1, n_2) of individual lenses of the doublet. We obtain

$$D_1 = n_2 \frac{1-\varphi D-\varphi s'_{F'}(1-\varphi_3 D)/n_3}{n_2\varphi_1 - n_1\varphi(1-\varphi_3 s'_{F'}/n_3)}, \qquad (1)$$

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$$\varphi_2 = \frac{\varphi - \varphi_3 - \varphi_1 + \varphi_1\varphi_3(D_1 + D_2)}{1 - D_1\varphi_1 - D_2\varphi_3(1 - D_1\varphi_1)}, \quad (2)$$

where $D_2 = D - n_1 D_1 / n_2$ and $D = d / n_2$. The unknown internal parameters can be calculated as

$$d_1 = n_1 D_1, \quad d_2 = d - d_1, \quad r_2 = (n_2 - n_1)/\varphi_2. \quad (3)$$

In case the values of refractive indices of lens materials are not known, then one has five unknown design parameters of the doublet, which has to be determined. It is needed at minimum five equations to determine these unknown doublet parameters. The required values of paraxial parameters f', s_F and $s'_{F'}$ of the doublet can be obtained with different combinations of design parameters n_1, n_2, d_1, d_2 and r_2. The solution is not unambiguous and thus one must use not only paraxial parameters, but also aberrations of the doublet. Using optimization techniques and Eqs. (1) – (3) one can calculate the unknown parameters n_1, n_2, d_1, d_2, and r_2.

In the case the wave aberration *W* is measured by the interferometer, which is a very precise method, then the merit function of the optimization problem can be chosen, for example, in the form

$$\Phi = \left(\frac{f' - f'_m}{\Delta f'}\right)^2 + \left(\frac{s_F - s_{Fm}}{\Delta s_F}\right)^2 + \left(\frac{s'_{F'} - s'_{F'm}}{\Delta s'_{F'}}\right)^2 + \left(\frac{W^{(\infty)} - W^{(\infty)}_m}{\Delta W^{(\infty)}}\right)^2 + \left(\frac{W^{(\infty)}_r - W^{(\infty)}_{rm}}{\Delta W^{(\infty)}}\right)^2, \quad (4)$$

where the subscript "*m*" denotes the measured parameter, the superscript "(∞)" means that the measurements or calculations are performed for the object at infinity ($s = \infty$), and $\Delta f'$, Δs_F, $\Delta s'_{F'}$, $\Delta W^{(\infty)}$, $\Delta W^{(\infty)}_r$ denote tolerances on corresponding parameters.

The investigated doublet is measured in one position (parameters f'_m, $s'_{F'm}$, $W^{(\infty)}_m$) and then it is measured in the reversed position (parameters s_{Fm}, $W^{(\infty)}_{rm}$). By this procedure one obtains all parameters needed for the evaluation of the merit function Φ. The calculation of parameters n_1, n_2, d_1, d_2, and r_2 is carried out using Eqs. (1) – (3) and global optimization techniques are used to calculate such values of refractive indices n_1, n_2 in order the merit function (4) was minimized.

4 Example

We will present an application of the described method on an example of determination of parameters of a cemented doublet. We consider that the refractive indices (n_1, n_2) of doublet materials are not known or measured. Using measured values (f'_m, $s'_{F'm}$, $W^{(\infty)}_m$) and (s_{Fm}, $W^{(\infty)}_{rm}$) in the merit function of the form given by Eq. (4) one can obtain the unknown parameters using optimization techniques.

Measurements of individual parameters of the doublets were carried out in laboratories of Meopta-optika company. Measurements of parameters f', s_F and $s'_{F'}$ were carried out using OTS 200 from OEG-Messtechnik, OptiCentric MOT 2R from Trioptic and the interferometer OWI 150 XT from Optotech. Wavefront measurements were performed using the interferometer OWI 150 XT from Optotech and the interferometer Zygo Verifire ATZ from ZYGO.

Measured values of parameters of the doublet were:

$r_{1m} = 57.036$ mm, $r_{3m} = -174.068$ mm,
$s'_{F',m} = 93.695$ mm, $s_{F,m} = -98.704$ mm,
$f'_m = 100.128$ mm, $W^{(\infty)}_m = -0.11\lambda$,
$W^{(\infty)}_{rm} = -9.21\lambda$, $\lambda = 546$ nm.

The nominal and calculated values of doublet parameters are given in Table 1.

Parameter	Nominal	Calculated
n_1	1.51874	1.5190
n_2	1.62409	1.6248
d_1	8.000	8.004
d_2	4.000	3.996
r_2	-40.738	-40.763

Tab. 1 *Nominal and calculated parameters of doublet (r_1 = 57.008 mm, r_2 = -40.738 mm, r_3 = -173.786 mm)*

As one can see the differences of the calculated parameters from the nominal parameters are small and the proposed method is efficient for the described problem of the determination of internal parameters of the doublet.

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