applied optics

Simple method for determination of parameters of cemented doublet

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This paper proposes a simple noninvasive method that makes it possible to calculate the inner design parameters of the cemented doublet using measurements of its chosen paraxial optical and geometrical parameters without any damage to the system under testing (e.g., dismantling). Derived formulas are based on the knowledge of measured values of the lenses thicknesses, the radii of curvatures of the first and the last doublet's surfaces, the paraxial focal length, and positions of the object and the image focal point. Practical usefulness of the proposed method is demonstrated on the real measurement of a known doublet.

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1. INTRODUCTION

In practical industrial applications the issue of determining the internal parameters of the optical system (e.g., photographic objective, etc.) without any damage to its components is in focus very often. The optical systems are usually composed by individual simple lenses or cemented doublets. A determination of parameters of simple lenses is very well known and it is an easily solvable problem, because one is able to measure the radii of curvatures of the lens' surfaces and the central thickness. Afterwards, the index of refraction can be calculated from the known formula for the optical power of the lens. A much more complicated issue comes to role with testing the cemented doublet if one wants to determine its internal parameters without any damage to the component, which is advantageous for practical purposes.

A cemented doublet belongs to frequently used optical systems in practice [1–6]. The doublet is composed of two spherical lenses, where the second radius of the first lens is identical to the first radius of the second lens, and both lenses are cemented together. In practice, it is possible to measure external parameters and aberrations relatively easily by various measurement techniques [7–14]. However, the internal parameters cannot be measured directly.

The authors' previous work [15] describes the possibility of determination of internal parameters of a cemented doublet, which is based on the measurement of paraxial parameters and wave aberration for a point on the optical axis of the doublet (spherical aberration). With regard to the fact that it is not possible to obtain a simple analytical solution for a determination of an unknown doublet's internal parameters, the optimization technique has to be used [16,17].

The aim of this work is to propose a novel and simple noninvasive method that makes it possible to obtain the internal design parameters of the cemented doublet using measurements of some paraxial optical and geometrical parameters of the doublet. The simplification of the previous procedure [15] is based on the measurement of internal thicknesses of the individual lenses, which can be by available commercial measurement devices, e.g., OptiCentric by the company Trioptics [13]. Such an approach provides a possibility to derive simple and explicit analytical formulas for the calculation of the remaining internal parameters only with the knowledge of the focal length, position of the object focal point, and position of the image focal point. Therefore, it is not needed to measure the wave aberration and calculate the internal parameters with complex optimization techniques, as it was necessary in the authors' previous paper [15].

2. DETERMINATION OF PARAMETERS OF CEMENTED DOUBLET

A scheme of the cemented doublet is shown in Fig. 1. Such an optical system 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 by. In Fig. 1, F and F' denote object and image focal point of the doublet, n_0 and n_3 are refractive indices of the object and image media, V_1 and V_2 are vertices of the doublet laying on the optical axis, s_F and $s'_{F'}$ are distances of the object and the image focal points from the vertices.

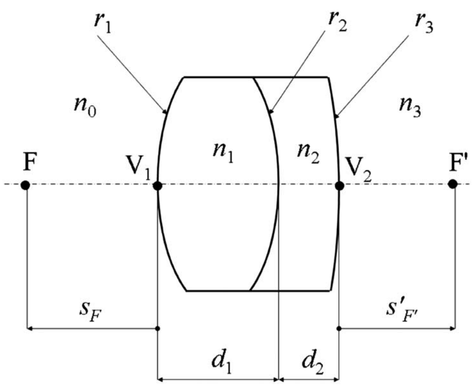

Fig. 1. Optical scheme of cemented doublet.

Using equations for paraxial ray tracing [1–6] one can derive the following formulas for optical power φ, position of the object focal point s_F, and position of the image focal point $s'_{F'}$ of the doublet. It holds:

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

$$s_F = n_0(D_1\varphi_2 + D_1\varphi_3 + D_2\varphi_3 - D_1 D_2 \varphi_2\varphi_3 - 1)/\varphi, \quad (2)$$

$$s'_{F'} = -n_3(D_1\varphi_1 + D_2\varphi_1 + D_2\varphi_2 - D_1 D_2 \varphi_1\varphi_2 - 1)/\varphi, \quad (3)$$

$$s' = \frac{n_0 n_3(D_1 + D_2 - D_1 D_2 \varphi_2) - s s'_{F'}\varphi}{\varphi(s_F - s)},$$

where s is the distance of the object from the first surface of the doublet, s' is the distance of the image from the last surface of the doublet. Optical powers $\varphi_1, \varphi_2, \varphi_3$ of individual refractive surfaces are given by the following formulas:

$$\varphi_1 = (n_1 - n_0)/r_1, \qquad \varphi_2 = (n_2 - n_1)/r_2,$$

$$\varphi_3 = (n_3 - n_2)/r_3,$$

and it holds for the reduced values of thickness D_1 and D_2:

$$D_1 = d_1/n_1, \qquad D_2 = d_2/n_2.$$

As one can see from Fig. 1, it is possible to measure relatively easily the radii of curvature r_1 and r_3, overall central thickness of the doublet $d = d_1 + d_2$, positions of the object and image focal points s_F and $s'_{F'}$, and focal length $f' = n_3/\varphi$ between the second principal plane and the image focal point F' of the doublet using the methods given, for example, in [7–15]. Next, it is possible to measure thicknesses d_1 and d_2 of the individual lenses using available commercial devices, e.g., Trioptics' OptiCentric [13].

Suppose now that the doublet is in the air, i.e., it holds for the object and image refractive indices $n_0 = 1$, $n_3 = 1$. Such a situation is the most common in practical situations. As was already stated in the introduction, the aim of this work is to determine the internal parameters n_1, n_2, and r_2 of the cemented doublet if one is able to measure radius r_1 of its first surface, radius r_3 of its last surface, thickness d_1 of the first lens and d_2 of the second lens, the focal length $f' = 1/\varphi$ (where φ is the optical power of the doublet when the surrounding media is air), position s_F of the object focal point, and position $s'_{F'}$ of the image focal point. The remaining parameters (n_1, n_2, and r_2) then can be calculated as follows.

Solution of the system of Eqs. (1)–(3) gives the following formula for the index of refraction n_2 of the second lens:

$$n_2 = \frac{d_2 + \varphi^2 d_2(s_F s'_{F'} + r_1 r_3 - r_3 s_F - r_1 s'_{F'})}{d_2 + r_3 - \varphi r_3(d_1 - r_1) + \varphi^2 s'_{F'}(d_2 s_F + r_3 s_F - d_2 r_1 - r_1 r_3)}. \quad (4)$$

Afterwards, the index of refraction n_1 of the first lens can be calculated as follows:

$$n_1 = \frac{\varphi d_1 n_2 r_3 (r_1 - s_F)}{r_1(d_2 n_2 - d_2 + n_2 r_3) - \varphi n_2 r_3 s_F (d_1 - r_1)}. \quad (5)$$

Finally, one can find the value of the second radius r_2 of the doublet with one of the following formulas:

$$r_2 = -\frac{d_1\left[\frac{d_2(n_2-1)}{n_2 r_3} + 1\right](n_1 - n_2)}{n_1\left[\varphi s_F + \frac{d_1(n_2-1)}{n_1 r_3} + \frac{d_2(n_2-1)}{n_2 r_3} + 1\right]}, \quad (6)$$

$$r_2 = -\frac{d_2\left[\frac{d_1(n_1-1)}{n_1 r_1} - 1\right](n_1 - n_2)}{n_2\left[\varphi s'_{F'} + \frac{d_1(n_1-1)}{n_1 r_1} + \frac{d_2(n_1-1)}{n_2 r_1} - 1\right]}. \quad (7)$$

In summary, one should follow the steps below for the calculation of inner parameters of the doublet:

1. The index of refraction n_2 of the second lens is calculated with Eq. (4).
2. Such a value is used in Eq. (5) and the index of refraction n_1 of the first lens can be calculated.
3. Using the values of indices of refraction in Eq. (6) or Eq. (7) gives the value of radius r_2 of the doublet.

The issue of inner parameters determination is therefore solved.

3. EXAMPLE

In this example the authors will present the proposed novel method of the calculation of parameters of the doublet in the case when the refractive indices n_1, n_2 and radius r_2 of the doublet are not known. As a comparison with the authors' previous method [15], the same cemented doublet will be used.

Consider a cemented doublet having the following nominal parameters: $r_1 = 57.008$ mm, $r_2 = -40.738$ mm, $r_3 = -173.786$ mm, $d_1 = 8$ mm, $d_2 = 4$ mm, $n_1 = 1.51874$ (Schott N-BK7), $n_2 = 1.62409$ (Schott F2) for the wavelength $\lambda = 546$ nm. Further, one obtains $f' = 100.029$ mm, $s_F = -98.603$ mm, $s'_{F'} = 93.599$ mm.

Measurements of individual parameters of the doublets were carried out in laboratories of Meopta-optika company [18]. Measurements were performed using several measuring instruments in order to obtain a higher reliability. Measurements of parameters f', s_F, and $s'_{F'}$ were carried out using OTS 200 from OEG-Messtechnik, OptiCentric MOT 2R from Trioptics, and the interferometer OWI 150 XT from Optotech. Measurements of the radii of curvatures were performed using the interferometer OWI 150 XT from

Table 1. Comparison of Nominal and Calculated Values of Inner Parameters of Cemented Doublet

	n_1	n_2	r_2[mm]
Nominal Values	1.51874	1.62409	–40.738
Calculated Values	1.51856	1.62373	–40.743

Optotech and the interferometer Zygo Verifire ATZ from ZYGO. The following values for individual parameters were obtained: $r_{1m} = 57.036$ mm, $r_{3m} = -174.068$ mm, $s'_{F'm} = 93.696$ mm, $s_{Fm} = -98.704$ mm, $f'_m = 100.128$ mm, $d_{1m} = 8.001$ mm, and $d_{2m} = 3.998$ mm. The accuracy of the measured parameters was as follows. The accuracy of the measurements of parameters f', s_F, and $s'_{F'}$ was $\pm 0.03\%$, the accuracy of the measurement of the thickness (d_1, d_2) was ± 0.001 mm with the use of the device Trioptics OptiCentric, and the accuracy of the radii of curvature measurement was ± 0.003 mm. Using the measured values and Eqs. (4)–(7) one can obtain the unknown parameters (n_1, n_2, r_2).

The nominal and resulting calculated values of the internal doublet parameters are given in Table 1. As one can see, the differences of the calculated parameters from the nominal parameters are very small, and the proposed method is efficient for the described problem of the determination of the inner parameters of the doublet in practice.

4. CONCLUSION

The paper presented novel and simple explicit formulas for the calculation of the inner parameters of a cemented doublet (n_1, n_2, r_2) based only on the knowledge of the first and back radii of curvature (r_1, r_3), central thickness (d_1, d_2), and the doublet's paraxial parameters, i.e., focal lengths f', position of the object focal point s_F, and position of the image focal point $s'_{F'}$. It was shown with the example of a real doublet that the proposed method is very efficient for the described issue of the determination of the inner doublet's parameters and that the method can find practical usage.

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REFERENCES

1. M. Herzberger, *Modern Geometrical Optics* (Interscience, 1958).
2. A. Mikš, *Applied Optics* (Czech Technical University, 2009).
3. M. Berek, *Grundlagen der Praktischen Optik* (Walter de Gruyter & Co., 1970).
4. M. Born and E. Wolf, *Principles of Optics* (Oxford University, 1964).
5. W. T. Welford, *Aberrations of the Symmetrical Optical Systems* (Academic, 1974).
6. A. Miks, J. Novak, and P. Novak, "Generalized refractive tunable-focus lens and its imaging characteristics," Opt. Express **18**, 9034–9047 (2010).
7. D. Malacara, *Optical Shop Testing* (Wiley, 2007).
8. G. V. Kreopalova, N. L. Lazareva, and D. T. Puriajev, *Optical Measurements* (Maschinostroenie, 1987).
9. J. Picht, *Meß- und Prüfmethoden der optischen Fertigung* (Akademie-Verlag, 1953).
10. J. Flügge, *Einführung in die Messung der optischen Grundgrössen* (Verlag Braun, 1954).
11. B. Dorband, H. Miller, and H. Gross, *Handbook of Optical Systems*, Vol. **5** of Metrology of Optical Components and Systems (Wiley, 2012).
12. http://www.zygo.com/.
13. http://www.trioptics.com/.
14. http://www.oeg-messtechnik.de/.
15. A. Miks and J. Novak, "Experimental method of determination of parameters of cemented doublet," Appl. Opt. **54**, 7940–7943 (2015).
16. L. E. Scales, *Introduction to Non-linear Optimization* (Springer, 1985).
17. E. M. T. Hendrix and B. G. Toth, *Introduction to Nonlinear and Global Optimization* (Springer, 2010).
18. http://www.meopta.com/en/.