*Witold Słówko**

On Compensation of Spherical Aberration in Electron Lenses by using an Electron Mirror

In this paper a method of spherical aberration compensation in electronooptical systems composed of electron lenses is described. The procedure consists in including an electron mirror in the system charged with the spherical aberration of sign opposite to that of the electron lens aberration. Basing on a two-lens system as an example a condition of compensation is given as well as fundamental limitations of the latter are discussed. Also, the structure and parameters of the experimental system as well as the results of experiments are described, which indicate a possible application of this system to the analysing electron microscope.

1. Introduction

A principal defect of electronooptical systems is the spherical aberration. It restricts the resolving power of such instruments used in research and technological examination like transmission and analysing electron microscope or electron beam exposurers, which are used in microelectronic element production. Since some scores of years an intensive study, aiming in the elimination of spherical aberration, is being carried out for electronooptical imaging systems. In spite of numerous concepts, that have been elaborated, positive results for practical solution of this problem have been achieved only for systems lacking in axial symmetry. However, such systems (for instance, system of quadrupole or octupole lenses) have not been widely used yet because of complex structure and high production cost.

2. Principle of compensation

In the electronooptic devices the imaging systems are mostly multi-lens systems. The influence spherical aberration of single lenses of the final image may be evaluated as it will be examplified on a two lens system consisting of "thin" lenses and presented in Fig. 1.

A point-object P is imaged by the lens S_2 in the form of an intermediate image O_p with a defect on the form of longitudinal spherical aberration Δa_p. This intermediate image is next imaged by the lens S_1 to produce the final image O which involves a simultaneous transformation of the defect Δa_p into Δb_2.

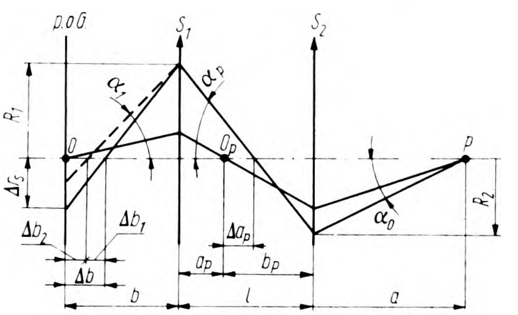

Fig. 1. Scheme of the two-lens system

As an additional error Δb_1 occurs due to spherical aberration of the lens S_1 the resulting error due to longitudinal spherical aberration Δb for the final image in the two-lens imaging system is a sum of both errors and may be written as follows [1].

$$\Delta b = \Delta b_1 + \Delta b_2 \simeq -(C^*_{s1} + M_1^4 C^*_{s2})\alpha_1^2, \quad (1)$$

where:

M_1 – linear magnification of the lens S_1,

α_1 – aperture angle of the beam in the final image space.

The coefficients C^*_{s1} and C^*_{s2} appearing in the relation (1) are modified constants of spherical aberration of lenses S_1 and S_2 which relate the spherical aberration defect in the image with the aperture angle of the beam

* Institute of Electronic Technology Wrocław Technical University, Poland.

in the image space if the image is positioned behind the lens focus.

The modified constant of the spherical aberration C_s^*, which was introduced by Petrie [2] is connected with the spherical aberration constant C_s, determined for the image located in the focal plane, according to the formula

$$C_s^* = C_s(M-1)^4, \tag{2}$$

where the linear magnification of the image M is less then zero for the reversed image.

On the base of the formula (1) it may be concluded, that if the spherical aberration constants of lenses creating the system under study are of opposite signs, then by a proper selection of the aberration values as well as that of the S_1 lens magnification, a complete compensation of the spherical aberration is achievable.

The compensation condition is as follows

$$C_{s1}^* + M_1^4 C_{s2}^* = 0 \tag{3}$$

some further analysis allows to infer that the compensation of the spherical aberration for the lens S_1 is possible only in lens central region of radius

$$R_{1\max} = \sqrt{\pm\left(1-\frac{l}{a_p}\right)\frac{b^4}{C_{s1}^* a_p}}. \tag{4}$$

The sign $(+)$ is valid for the range $a_p > 1$, while the sign $(-)$ holds for $a_p > 1$. Thus the last dependence determines – in accordance with the notation accepted in Fig. 1 – the maximum crossover of the lens S_1 in the compensated two-lens system.

The fulfillement of the compensation condition for spherical aberration in the two-lens system does not assure a true imaging, even if no errors other than spherical aberration are present. This is because an image deformation may be expected, which resembles magnification error and is essentially a difference between the size of the image produced by paraxial rays and that produced by marginal rays [2]. A relative defect of linear magnification (or size defect) in the image is defined by the relation

$$\frac{\Delta h}{h_0} = \frac{\Delta M}{M_0} = \left\{\frac{a_p}{l}\left[\frac{(l-a_p)b^4}{C_{s1}^* R_1^2 a_p^2}+1\right]-1\right\}^{-1}, \tag{5}$$

where h_0 and M_0 denote, respectively, the size and linear magnification of the image for paraxial trajectories.

From [5] it may be concluded that by satisfying the compensation condition for spherical aberration (3) a defect-free imaging of a point-object of infinitesimally small dimensions becomes possible. An elimitation of this magnification error is possible in the case when

$$\frac{a_p}{l} = \pm\infty, \tag{6}$$

i.e. if the lenses of the system coincide with each other ($l = 0$) or if the object is located in the focus of the lens S_2, while the intermediate occurs at infinity.

In spite of such radical limitation in applicability the problem of spherical aberration compensation in the two-component system is not totally impractical. It may be of some importance for a whole class of devices employing electron "microbeams" such as analysing electron microscopes.

In such system the imaging is expected to assure a respectively small beam diameter, while a true transfer of detailed information about the object (which in this case in an electron crossover) is of no essential meaning.

In this case instead of eliminating the magnification error it suffices to make its relative value negative. Then an erroneous image produced by rays, travelling far from the axis has sizes less than the proper dimension, and the maximum beam diameter in the image plane is determined by the paraxial trajectories.

The magnification error takes a negative value, when $a_p > 0$ i.e. when the intermediate image occurs in the space of final image, or if $a_p > 1$, i.e. if the intermediate image appears in the object space.

3. Experimental compensation of spherical aberration

Classical electron lenses of rotational symmetry are characterized by positive spherical aberration. Thus in order to compensate a two-lens system, one lens should be replaced by an electronooptical element suffering from a negative spherical aberration. Such an element may be an electron mirror.

The first suggestion of applying an electronooptical mirror to compensate a spherical aberration of electron microscope objective was presented by Zworykin in [3]. This proposal was widely criticized and did not find any experimental confirmation till now due to lack of the electronooptical mirror of sufficiently high value of the spherical aberration constant [4].

In the case of mirrors there exists a possibility of manoeuvering with electronooptical parameters in a highly wider range that it is possible for electron lenses [5]. Therefore, we decided to design an electron mirror of sufficiently high spherical aberration in order

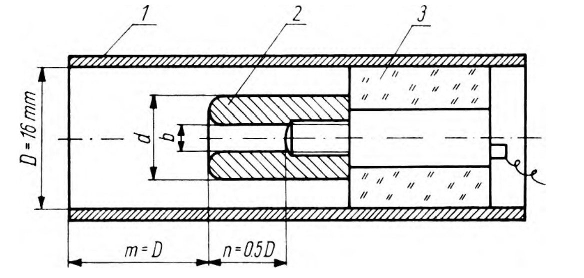

Fig. 2. Two-tube mirror
1 – accelerating electrode, *2* – decelerating electrode, *3* – isolator

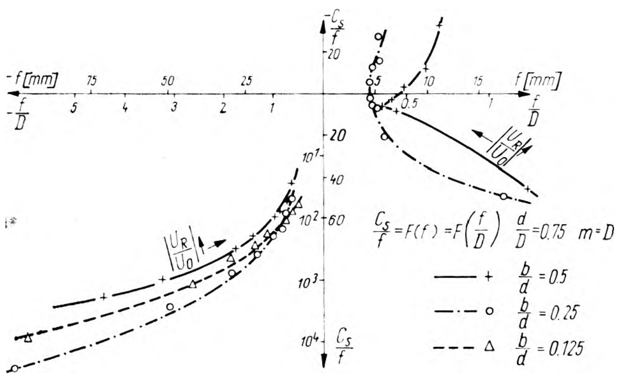

Fig. 3. Dependence of the reduced constant of spherical aberration on the focal length for two-tube mirror

to perform the intended compensation. The most advantageous results were obtained in the case of two-tube mirror with a thick decelerating electrode of construction shown schematically in Fig. 2 [6]. The characteristics of the reduced spherical aberration constant as a function of focal distance are presented in Fig. 3.

Hence, it may be concluded that both the sigh and the spherical aberration value of a two-tube mirror are sufficient within the region of divergence to compensate spherical aberration of the electron lenses of both magnetic and electrostatic types.

Electrostatic electron lenses exhibit much greater spherical aberration than the magnetic lenses and therefore they are rarely applied in the electronooptical devices. However, the electronooptical systems built out of such

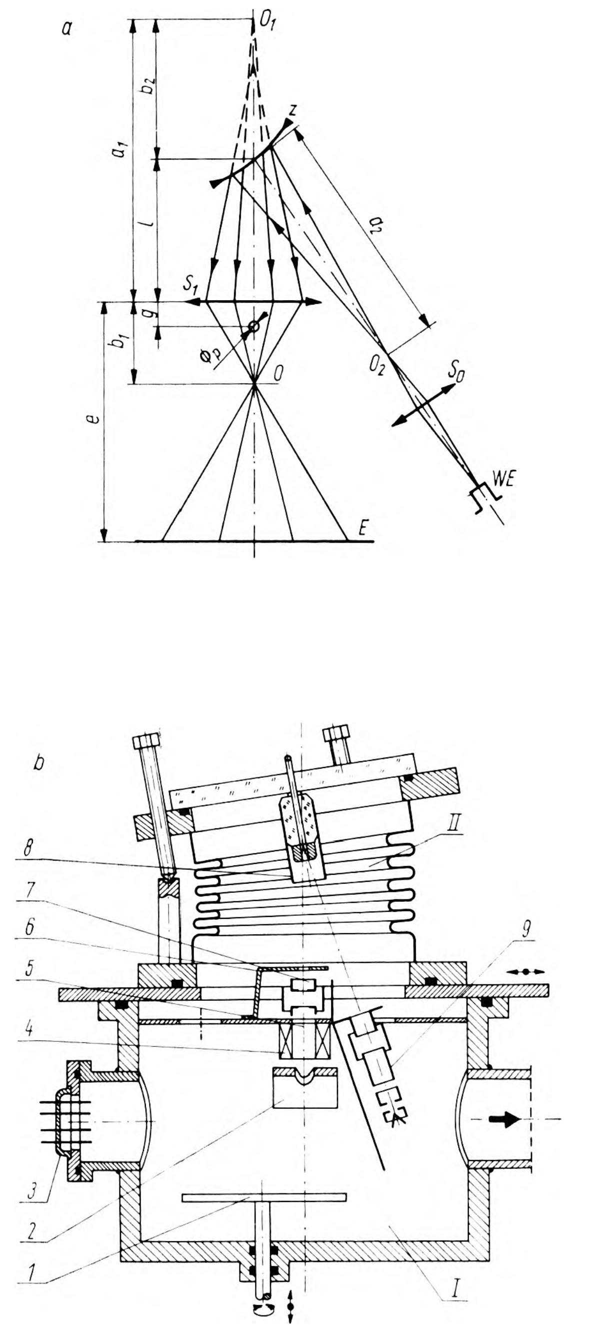

Fig. 4. Imaging system of compensated spherical aberration
a – electron beam trace,
b – construction scheme
1 – screen, *2* – mirror for photography, *3* – electric through put, *4* – deflecting system, *5* – measurement rod, *6* – auxiliary screen, *7* – objective lens, *8* – correcting mirror, *9* – electron gun with condenser lens

lenses offer numerous advantages like: small sizes, simple structure, a possibility of supplying all the elements from one voltage source by a proper voltage divider and finaly far weaker requirements concerning the necessary stability of the source (by two orders of magnitude).

For these reasons we have decided to undertake the task of compensating the spherical aberration with the help of an electron mirror in a model system composed of electrostatic lenses, though the available range of compensation [4] is lower for the lenses of this type than for magnetic lenses due to spherical aberration constants. The model system should face demands similar to those met by imaging systems of the electron beam devices (for instance $M \ll 1$ [7]).

The construction of te model system is shown in Fig. 4 a, b. The electron beam emerging from the electron gun WE passes the region of the lens S_0 called condenser lens, which produces an intermediate image O_2 of the electron gun crossover. Next, the beam hits the correction electron mirror Z, which gives another intermediate image O. The final image O is a product of the lens S, called an objective, which acts on the electron reflected from the mirror. The magnifications and spherical aberration constant., of both the objective lens and correction mirror should be chosen in such a way that the condition (3) of spherical aberration compensation be fulfilled. As the magnifications of both the elements are related by the compensation condition the adjustment of the total magnification of the whole system as well as the regulation of the resulting beam diameter may be made only by changing the magnification of the condenser lens.

This lens should be of short focal distance so that the required changes in magnification do not influence essentially the position of the intermediate image O_2 with respect to the mirror.

The role of both the electron gun and the condenser lens in the model system is played by the electron gun used in the AW-47-91 kinescopes, in which the oxide cathod was replaced by the wolfram cathod. An electrostatic lens shown in Fig. 5, which was also taken from the AW-47-91 kinescope gun, was applied an objective lens.

Now, assuming — in accordance with the notation used in Fig. 4a — that the distance of the final image from the objective lens should be $b_1 = 50$ mm and the magnification of the lens should amount to $M_1 = -0.3$, the focal distance and the spherical aberration constants measured by the shadow method are

$$f_1 = 40 \text{ mm}, \; C_{s1} = 960 \text{ mm}, \; C^*_{s1} = 2.9 \cdot 10^3 \text{ mm}.$$

Then, the modified value of the spherical aberration constant for the correcting mirror evaluated from te compensation condition amounts to $C^*_{sz} \simeq -3.6 \cdot 10^5$mm, which in the face of (2) gives $C_{sz} \simeq -6 \cdot 10^6$ mm, when assuming that the mirror magnification $M_z = 0.5$.

From the characteristics shown in Fig. 3 it follows, that, in practice, such high values of spherical aberration constants were not obtained in the region covered by the measurements. However, if an extrapolation of these

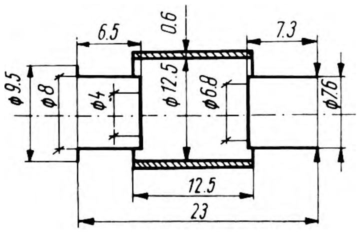

Fig. 5. Objective lens scheme

responses be made toward long focal lengths it is clear that the needed values of the spherical aberration of the two-tube mirror may be expected for the focal length satisfying condition $-f/D \simeq 10$.

Hence, it follows that the distances between the system elements marked in Fig. 4a should take the values as listed below:

$$b_1 = 50 \text{ mm}, \; l = 95 \text{ mm},$$

$$b_2 = 75 \text{ mm}, \; a_2 = 150 \text{ mm}.$$

The spherical aberration of the condenser lens may be neglected because the magnification M of the system objective lens — mirror is much less than unity ($M \ll 1$).

In order to control the compensation of the system a rod of 0.2 mm diameter as well as a luminescence screen E were placed below the objective lens. The distances of these elements from the middle point of the objective lens are $g = 11$ mm and $e = 97$, respectively. The compensating procedure for spherical aberration of the system consisted in a proper solution of the potential U_r of the decelerating electrode in the correcting mirror (accelerating voltage $U_0 = 4$ kV). The shadow images of the

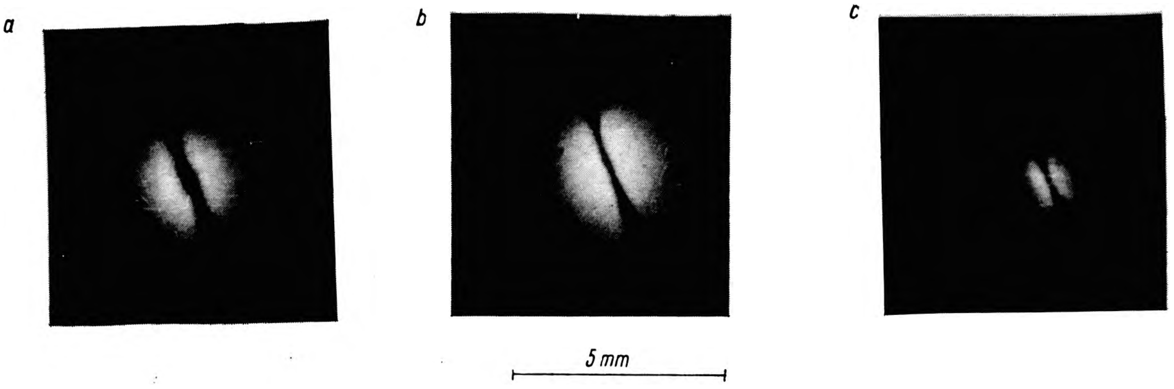

Fig. 6. Shadow image in successive compensation phases
a — overcompensated system, b — compensated system, c — undercompensated system

measurement rod were photographed for the subsequent phases of compensation. The photographs of the shadow images for the three subsequent compensation phases are presented in Fig. 6a, b, c. The sizes of the obtained shadow images are small, which in junction with the low resolution of the electroluminescent screen results in reduced definition of these images. In spite of this, the interpretation of the photograms presented should not render greater difficulties.

The first of the shadow images (a) was obtained at the relative voltage value $U_r/U_0 = -0.205$ of the mirror decelerating electrode. In the central part of the image an increment of the shadow occurs, which indicates a positive spherical aberration, while in the outer zone the aberration is negative. Thus the respective constants of spherical aberration are of opposite signs. Hence, it follows, that the imaging system is overcompensated. The next photogram (b) shows the case of system compensation achieved at $U_r/U_0 = -0.210$.

The fact that compensation of spherical aberration really takes place may be concluded from the equal width of the shadow in the central part of the image (a slight overcompensation is, however, visible). The last of the images (c) is obtained at $U_r/U_0 = -0.25$ and shows an uncomplete compensation of the system, because a deformation typical of negative spherical aberration is observable in the whole region.

An analysis of the shadow image obtained under the compensation condition indicates some deviations of the system parameters from the values assumed formerly though a generally satisfactory agreement has been achieved. Namely, the region of the shadow image exhibiting good compensation (central part of 13 mm diameter) corresponds to the radius of the objective lens crossover $R_1 = 0.7$ mm and to the 0.014 rad aperture angle of the beam. The maximal value of the lens crossover radius in the compensation zone estimated from the formula (4) by substituting the assumed values is $R_{1\max} = 2$ mm. Divergence between both the results may be explained by both the simplified assumption adopted during derivation of (4) and the inaccuracy of determining the real parameters of the system.

4. Conclusions

Though a relatively narrow compensation zone was achieved in the experimental system the measurements results should be considered as adventageous for applications. The application of compensated imaging system to be promising in the analyzing electron microscopy.

In order to obtain a sufficiently narrow beam (of 1 μm–0.01 μm diameter) it is necessary to keep the aperture angle of the beam very small ($\alpha_1 \approx 10^{-3}$) because of spherical aberration. This is connected with application of small diameter diaphgram and a drastic reduction of beam current (10^{-11}–10^{-8} A).

Compensation of spherical aberration even in such a narrow zone as that appearing in the described experiment allows to increase the beam current by several orders of magnitude. In this way the time of the object analysis is considerably shortened while the image quality is improved. On the other hand, the compensation of the spherical aberration enables constructing of an imaging system composed of electrostatic lenses which offers additional advantages of both technical and economic nature mentioned above.

Compensation d'aberration sphérique d'une lentille électronique à l'aide d'un miroir électronique

On a décrit une méthode de compensation de l'aberration sphérique dans les systèmes optiques électroniques composés des lentilles électroniques. Cette méthode réside à brancher dans le système un miroir électronique à l'aberration sphérique d'une charge électrique contraire que celle de l'aberration des lentilles électroniques. À l'example d'un système de deux lentilles on a établi non seulement conditions nécessaires pour que la compensation ait lieu et mais aussi les limitations principales de sa réalisation. On a également décrit la construction et les paramètres d'un système experimental et les résultats de l'expérience, indiquant une possibilité d'application du système dans un microscope analytique électronique.

Компенсация сферической аберрации электронной линзы с помощью электронного зеркала

В работе описан метод компенсации сферической аберрации в электронно-оптических системах, состоящих из электронных линз. Этот метод состоит в включении в систему электронного зеркала со сферической аберрацией противоположного знака, по сравнению с абберацией электронных линз. Опираясь на пример двухлинзовой системы было определено условие компенсации и основные ограничения в её осуществлении. Возможность компенсации была подтверждена экспериментальным путём. Описаны также строение и параметры экспериментальной системы, а также результаты эксперимента, при указании на возможность применения системы в электронном анализирующем микроскопе.

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