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MEASUREMENT OF ABERRATIONS OF PHOTOGRAPHIC LENSES.

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This paper deals with the measurement of the aberrations of photographic lenses from the point of view of the designer, and so will not deal with such methods as give the performance of the lens without furnishing numerical estimates of its aberrations.

In the first place it is important to be able to compare the actual performance of a lens with the numerical measure of its aberrations in order to obtain the limits of error permissible in the various aberrations when calculating a system. Again, the verification of the aberrations of a system by trigonometrical calculation is very laborious, and may frequently be avoided if it is possible to make the lens and measure its aberrations.

It is thus evident that there are considerable advantages in measuring the aberrations of a photographic lens, provided the results can be so expressed as to give the same results as would be given by calculation, and it be possible to deduce aberrations at intermediate points of field, or aperture, from the actual measurements.

The theory of aberrations shows that to the first approximation the performance of a system may be represented (omitting chromatic effects) by five aberrations, generally described as spherical aberrations, coma, astigmatism, curvature of field, and distortion. These aberrations may be expressed as absolute or relative aberrations, the latter being pure numbers indicating the correction of the system. For a detailed discussion of the expressions of these aberrations and their relation to one another, a paper by Dr. Drysdale, at the Optical Convention†, may be referred to.

For our present purpose it is important to note that of these first order aberrations, the spherical aberration varies as A^3, the coma as $A^2 \tan \theta$, the astigmatism and curvature of field as A tan $^2\theta$, and the distortion as tan $^3\theta$, where A represents the aperture ratio and θ the semi-angle of field considered.

But though the aberrations of the single lens may be regarded as approximately equal to the first order aberrations and so be analysed in the way indicated above, it must be remembered that in practical systems the first order aberrations have been approximately balanced, while those of the second order have been left to take care of themselves, with the result that, in most practical systems, the second order aberrations bear a very much larger ratio to the first order than they do in single lenses, and that a small change in the system will have a considerable effect on the first order aberrations, and very little on the second.

Thus, although the second order aberrations are not proportional to the aperture and field in the same way as those of the first order, it is frequently convenient to represent them in the same way, indicating them by the first order aberration which would produce the same effect at full aperture or full angular field, because the best correction of the second order aberrations is generally produced by leaving a first order aberration of this amount, but of opposite sign, to balance the effects of the second order aberration.

But, while this representation is convenient for many purposes, it is frequently very important to be able to obtain the "run" of the aberration throughout field or aperture as well as the amount of its greatest value. Two methods of representation have been proposed—both graphical. In the first, the aberrations expressed as longitudinal or lateral aberrations are represented by the ordinates of a curve, as in von Rohr "Die Photographischen Objective," where the spherical aberration and the astigmatism and curvature of field, obtained by calculation, as longitudinal aberrations, are so repre-

† Dr. C. V. Drysdale, Measurement of Aberrations. Proc. Optical Convention, 1905.

sented. In the other method, described before the Optical Convention‡, the lateral aberrations for certain chosen rays obtained by calculation or measurement, are indicated by the distance between two points, the position of the ray as regards the axis being indicated by the position of one of these points (or, where aberrations are large, the mean of the two points). This method has the advantage that any defect due to the combination of two aberrations is apparent, while the effect of each portion of the aperture for any chosen field can be seen from the diagram, whereas, in the method generally used the astigmatism and curvature must be calculated for a specified aperture, and change of aperture will frequently affect the form of the curve.

In using these graphical representations it is necessary to arrange the methods of measurement so that the results are readily expressible in the desired form.

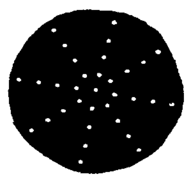

FIG. 1.

For practical measurements there are three principal methods depending on—

(1) The measurement of the size of the image formed on the focal plane, accompanied by some estimate of the distribution of light in this image.

(2) The determination of the positions of best focus for suitable objects.

(3) The evaluation of the positions in which specified sample rays cross the focal plane or any plane parallel to it.

The first of these methods gives most information as to the actual performance of the system under the given conditions. But it is very difficult to differentiate between good lenses, or to obtain a numerical estimate of the performance of the lens. It is quite unsuited for

‡ S. D. Chalmers, Aberrations. Proc. Optical Convention, 1905.

testing the performance of partial systems not completely corrected.

Again, it is practically impossible to determine the cause of given defects and so furnish the information the designer wants, while the choice of focus depends on the personal equation of the observer, and the measurements give no means of estimating the effects of an alteration of focus.

The second method avoids this last difficulty; it gives some information to the designer as to the cause of errors, but it does not give, except under unjustifiable assumptions, a means of obtaining the actual performance. It is defective because there is in general no definite sharply defined focus even for a series of parallel lines, and it is frequently possible to choose two positions

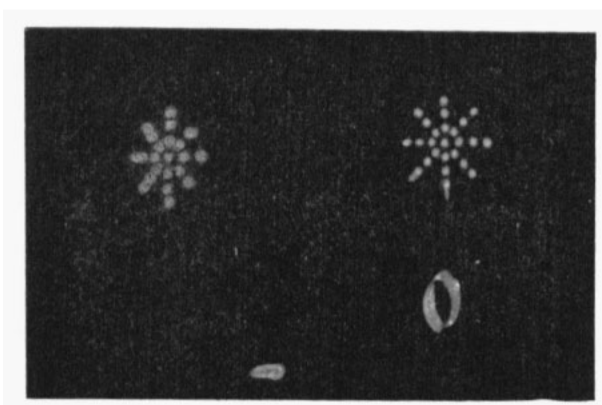

FIG. 2.

of focus so far apart that one estimate of the aberration is twice the other. This may be specially marked for large apertures at moderate angles of field.

In both methods the results, when obtained, are suitable for expression as curves; in the first the lateral, in the second the longitudinal aberrations being the ordinates of the curves.

In the third method the performance of the system is not given directly, and it can only be deduced from the aberrations as measured, but it can be made to show first order and second order aberrations separately; it shows the effects of combined aberrations of the second order. It gives the coma both of first and second orders with an accuracy unattainable by other methods. It is suitable even for totally uncorrected systems, and its results are at once expressible in the diagrammatic form indicated above.

It now remains to describe the actual methods employed in obtaining the measurements according to each of these principles, and the apparatus and methods in use at the Northampton Institute will be taken as convenient illustrations.

TESTING METHODS IN USE AT THE NORTHAMPTON INSTITUTE.—For all measurements the Beck lens testing bench is used. When the lens is to be used for near objects the standard test of the bench* is used, but for lenses to be tested on distant objects we employ the special swinging test, in which the image is examined on the focal plane or the small departures of the best focus from that plane are directly measured.

It may be interesting to see how this test was devised. When the lens-testing equipment of the Northampton Institute was being specified it occurred to me that the troublesome reductions of the ordinary tests might be avoided if the measurements could be made from the proper point on the focal plane and not from a fixed point. The original intention was to place a test object on the focal plane and to examine this object by the lens and a telescope, observing the focusing motion, either in the telescope or lens, necessary to obtain best general focus, or the best focus for special lines of the test object. But difficulties of illuminating the object evenly and satisfactorily caused Mr. Horace Beck to reverse the test by placing a microscope on the bar in such a way that it remained focused on the focal plane of the lens when the lens was rotated about a vertical axis. The convenience of this test is so great that it has become the standard test for lenses which are used for distant objects.

In using this test the lens is screwed into the lens holder, the observing microscope is brought to a standard position, the plate carrier racked till the image of the

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* Photographic Lenses. Beck and Andrews. Appendix.

distant object is sharply focused. The lens holder is swung about the vertical axis and the whole of the carrier racked till the image comes back to its original position in the field of the microscope. On swinging the lens the image should be practically stationary, and a very slight adjustment enables the nodal point to be set exactly above the axis of rotation. The distance from the centre of rotation to the plate carrier can be read off on a suitable scale and gives the equivalent focal length.

SPHERICAL ABERRATION.—To measure the spherical aberration the focusing positions for different zones may be measured by the aid of a set of patch stops, but it is more convenient to measure the diameter of a patch of light which is obtained when a small circular aperture of known dimensions is used as source (where light is a consideration the aperture may be of considerable size and the difference between the theoretical and observed size noticed). For this and similar measurements the microscope is provided with a micrometer eye-piece reading to .1 mm., and corresponding to 1/150 mm. with the objective usually employed.

COMA.—This aberration is shown by a one-sided appearance of the image, but it is not possible, in the ordinary way, to obtain a numerical estimate of the coma, because the figure seen is invariably complicated by the presence of astigmatism and curvature of field, and the complicated effects of combinations of these aberrations render analysis difficult, and the use of objects giving finite images would still further complicate the reductions.

ASTIGMATISM AND CURVATURE OF FIELD.—If there were no coma (as is the case in most double symmetrical systems), the astigmatism and curvature of field could be deduced from measurements of the diameters of the elliptic patch on the plate, or from the measurements of the best focusing positions for horizontal and vertical lines. But in practice there is considerable latitude in the choice of the position of best focus, because the presence of spherical aberration at any angle causes portions of the aperture to give good foci in different places. In spite of these difficulties, however, it is possible to obtain sufficiently accurate results for systems of the same type, to enable us to compare the performance of an individual member with the standard by either of these methods. Thus, for manufacturing purposes it is unnecessary to use more elaborate tests, except for isolated samples.

DISTORTION is most conveniently estimated by the actual movement, in the field of the microscope, of the image when the lens is swung. (This presumes great accuracy in the apparatus.)

THE HARTMANN TEST.—This method, which was devised by Professor Hartmann, has been described by him in the 'Zeitschrift für Instrumentenkunde,'† and by the author in the Proceedings of this Society and elsewhere.‡

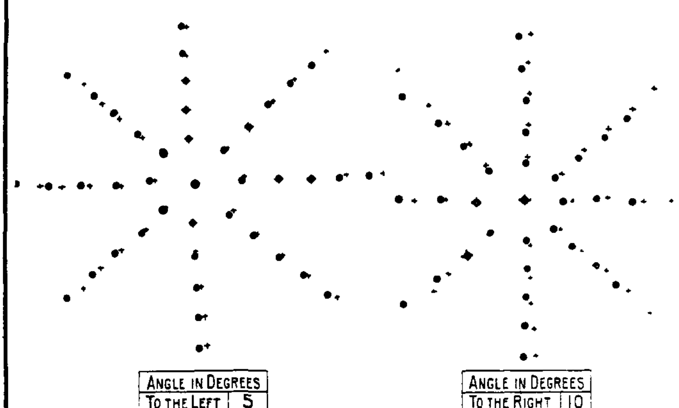

FIG. 3.

The author's modifications of this method have been directed to the simplification of the measurements of the photographs taken in accordance with Hartmann's method, and the expression of the results in diagrammatic form. In order that this diagram may be suitable for the deduction of the first and second order aberrations as separate quantities it is necessary that the diaphragm should be reasonably well centred and symmetrical about

† 'Zeitschrift für Instrumentenkunde,' translated by the OPTICIAN AND PHOTOGRAPHIC TRADES REVIEW.

‡ Proc. Optical Society, 1904. Journal of the Royal Photographic Society, March, 1905.

the axis, and should be in the plane of the effective stop. For lenses to be tested on distant objects a collimator is used and the lens rotated about a vertical axis, which is

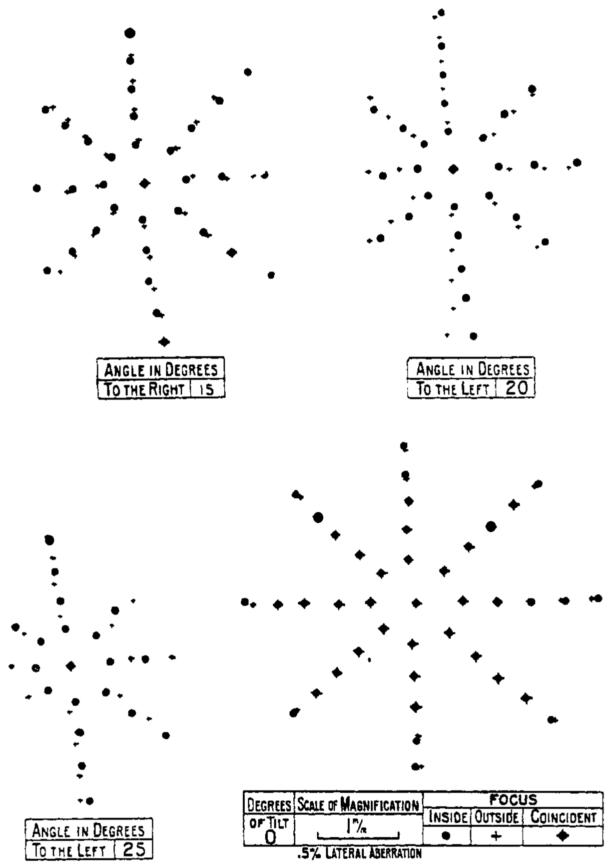

Fig. 3—(*Continued.*)

for convenience made to coincide with the nodal point of the lens. (Where the collimator is in any way defective it would be preferable to arrange to rotate the lens about a vertical axis passing through the "entrance pupil" of the lens, *i.e.*, the image of the stop in the front medium—in double symmetrical systems the front nodal point.)

In ordinary practice the swinging test fixture of the Beck bench is used, the position of best central focus determined and the two series of photographs taken from 2 to 3 cm. inside and outside focus—the two distances being made as exactly equal as possible. When an arc lamp is used to illuminate the collimator aperture, approximately 1 mm. diameter, the exposures necessary are less than 1 second, though a considerable amount of over-exposure is desirable, as this brings out the diffraction rings and makes the photographs easier to measure. The stop employed is usually made of brown paper or thin metal, the apertures being stamped; it is usual to arrange the apertures in four lines, horizontal, vertical, and at 45°, giving eight apertures in a ring of 6 mm. diameter, and as many rings as possible, each diameter being 6 mm. greater than the one preceding.* Fig. 1 shows the contact print of an actual stop, and fig. 2 the photographs taken with this diaphragm. These photographs have been enlarged 5 times, to show the detail of the photograph and the sharpness with which the spots are defined.

The photographs so obtained must be enlarged for comparison purposes, but it is found convenient to draw out the centre of each of the spots by the aid of a microscope and camera lucida, the magnification being from 30 to 50 diameters; it is found convenient to obtain as much as possible of this magnification by projecting the image as far as possible, as this enables a larger field to be conveniently seen and illuminated. When one diagram has been drawn off completely, the other photograph is reversed, and its image made to overlap the corresponding diagram; the distance between the corresponding points, then, represents the lateral aberration on a scale of 2 m.: 1 or, if the two photographs are differently magnified, *i.e.*, a focus different to that selected visually decided upon, $m_1 + m_2$: 1. Fig. 3 is a complete diagram for a good anastigmat in which the original magnifications were each 35, and so reduced

* For smaller lenses 5 mm. or even 4 mm. intervals are preferable.

that the lateral aberrations are represented on the scale of 24 : 1.

These illustrations show that the aberrations are diagrammatically represented as described above; the cutting off is shown and the aperture ratio to which the various rings correspond given by their diameter divided by m times the distance between the photographs.

In the central photographs the two diagrams coincide within the limits of error in drawing, but at 10° a considerable amount of coma is noticeable, while a small amount of astigmatism can be seen; the exact amounts are difficult to measure because of the comparatively small magnification of the drawing in this special case.

In order to express the aberrations in the form of curves, the astigmatism can be deduced as a lateral aberration by considering the outside apertures for the vertical and horizontal lines, the sum of the aberrations for the vertical gives the vertical diameter of the image of a point, while the horizontal give the horizontal diameter, and from these two quantities the astigmatism and curvature for the aperture and field considered may be deduced. It is, however, important to note that for any special aperture the effect of spherical aberration and of curvature of field are identical, and it is necessary to consider either different angles of field or different apertures before these effects can be differentiated.

It is important to note that any difficulties of this kind will apply to the results of calculation (by trigonometrical methods) equally with the measurement results.

Thus, this method of measurement and representation makes the results strictly comparable with the results of trigonometrical calculations, and give all the desired information about the lenses.