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Lens Testing or Image Evaluation?

Lenses need to be tested in ways similar to the methods used in lens design so that the designers can obtain accurate information.

Abstract: *The mathematical concept of an Optical Transfer Function in optical system evaluation is now widely understood and is being used extensively in specifying and analyzing lenses. Most optical designers are now able to calculate the OTF of their designs. Several instruments which measure the OTF are commercially available. It would be appropriate to standardize on several of the definitions in this field and record in one document the acceptable procedures for measuring OTF. The British Standards Institution has prepared a draft of a British Standard, which is a major step towards meeting the need. It is perhaps written too much around one particular method for measuring OTF. It should be possible to write the standard to encompass the basic principles and allow a wide variety of methods. There is need, however, for further development in the use of OTF measurements. The present OTF test equipment supplies the user with a larger number of OTF curves for several focus and field positions. In order to decide if a lens is acceptable, it is necessary to reduce all the data to a single "figure of merit" for the optical system. Acceptable merit functions for a lens are needed far more than new variations on how to measure OTF.*

Where Do We Stand With OTF?

OTF, MTF and PTF concepts for image evaluation are now well known. Hundreds of papers have been written on the subject. Numerous methods for measuring these quantities have been discussed thoroughly, criticized and defended. Where comparative measurements are made on the same image, there is good agreement between different laboratories. Most of the disagreement between laboratories involves the metrology and has nothing to do with the concept of OTF. The metrological problems in testing a lens are difficult and are usually underestimated. OTF has proven to be a valuable tool to use in defining an image. It has contributed little to overall lens evaluation.

In spite of the success of OTF, the actual use of OTF has been limited. Most of the practical methods of lens testing use the reading of resolving power charts. OTF testing seems to be confined to work done on well-financed government projects. The uses of MTF data impress the experienced optical man or lens designers as window dressing. I feel safe in making such a heretic statement because I have been through it before, in learning how to design lenses.

Prior to the large computer, lens design was done by computing the path of an extremely limited number of rays. Many curves were drawn by the lens designer

* Presented at the 12th Congress of the International Society of Photogrammetry in Ottawa, Canada, July 1972, under a different title.

showing how spherical aberration varied with aperture, how coma changed with field angle. Each designer had a favorite set of indicators of performance. In most instances, all the curves did not lie perfectly flat, whereupon compromises had to be made. At this point the science ended and the art began. The designer would select some assortment of wiggly curves and declare them to be the best that could be done. To challenge him meant hours of computing and inventing a new set of criterion on how the wiggly curves should look. It was not until the computer came into general use that this changed. The computer could not find optimum solutions until the program writers defined precisely a criterion for image quality. Once the computer had a definition, it had no difficulty finding the best lens from among a group of lenses.

Lens testing, even with OTF, seems to be back in the dark ages of having experts look at wiggly curves to evaluate lenses and rank them in quality. With the experience of observing the impact that computers have had on lens design, it is safe to speculate that OTF will never contribute appreciably to objective lens testing until the compter is involved in the test.

When OTF fans face the fact that this concept is of little value in lens testing until one can define a single *Figure of Merit* (FOM), they will also realize that OTF, line-spread function or encircled energy are merely similar quantities. The fundamental contribution to lens testing and evaluation comes about from having measured directly the light concentration in the image. Objective testing now seems to be feasible because the light concentration can be measured, and the computer can handle in a reasonable time the large amount of data collection and computation involved. Where we stand with OTF lens testing can be summarized as follows:

- The computer is the major potential contributor for an objective evaluation of lenses.
- OTF graphs provide no appreciable aid to the lens inspector who is asked to pass judgement on the quality of a group of lenses. If adequate computer support cannot be provided to solve the complicated simultaneous equations involved, it will remain more expedient for the operator visually to inspect targets, scenes, or point source images.

Test Equipment Needed to Test a Lens

This section describes the basic components needed to test a lens and assign an FOM so that the lens can be compared with other lenses or with the original design. It is assumed that the lens works at finite conjugates.

THE OBJECT REFERENCE SURFACE

There should be a flat object reference plane to position several point sources. Locating point sources in a single plane represents a substantial mechanical problem. These problems and expedient compromises will be discussed in a later section.

IMAGE REFERENCE PLANE

It is necessary to measure the OTF of the object plane point sources in the flat image plane.

FLANGE LENS-MOUNTING PLANE

Between the object and image plane there must be a flange mounting for mounting the lens.

THE COMPUTER

There should be a computer to gather and process the data.

The three planes must all be parallel. The four components are illustrated in Figure 1.

The Test Procedure

1. Insert the lens with its mounting flange in position against the lens reference plane.
2. Measure the line-spread function or edgetransition curve for each of the object points for both a radial and a tangential scan. Store these data in the computer memory along with the position coordinates of the image. (Definition of where the image lies is open to discussion). Use nearly monochromatic light.
3. Change the wavelength and repeat Step 2 for five to seven wavelengths distributed over the useful spectral range.
4. Shift the image plane towards or away from the object plane while maintaining strict parallelism.
5. Repeat Steps 2, 3, 4 until from 5 to 10 focal shifts have been made.
6. Repeat steps 2 to 5 for a second object plane.
7. The computer must then process the data in the following way:

7.1 For each image point the spread functions in each wavelength must be convolved after they have been adjusted to account for the source and detector sensitivity.

7.2 Once the white-light spread functions have been computed, the OTF can then be computed for each of the image points.

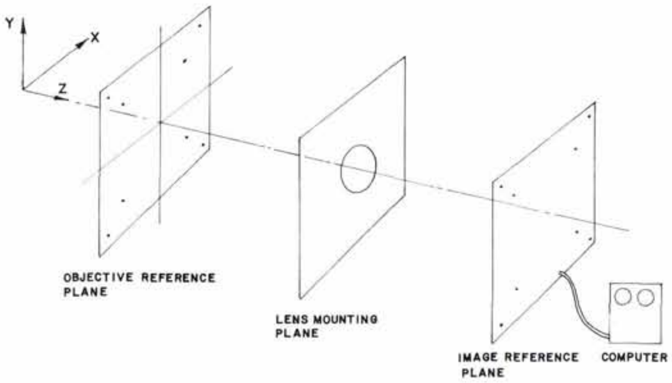

FIG. 1. Schematic diagram of basic reference planes for finite lens testing.

7.3 The computer must then compute an FOM for all the images on each of the focal planes. Dutton[1] has recently described several FOM for use in lens evaluation. The computer can compute alternate FOM's to suit a particular user's preference. Dutton includes phase as a penalty term in his FOM. It is interesting to note that lens designers have avoided the phase problem of OTF by penalizing unsymmetrical imagery. Their automatic correcting programs have strong tendencies to eliminate these kinds of errors. The lens testing community, however, is faced with lenses which have decentering errors due to manufacture, which introduces unsymmetrical images. The phase term cannot be ignored for it most certainly degrades the len's performance. The irony of the situation is if lens designers eliminate unsymmetrical image errors they often design lenses which are sensitive to tilt and decenter. The manufactured lenses then have unsymmetrical image errors which the testing people also want to ignore. This divergent looping needs closing.

7.4 Finally, the computer should solve for the optimum image plane tilt to maximize the FOM, subject to the constraints that the magnification and keystoning be within tolerance.

It is immediately apparent that the above testing program represents an immense amount of data collection. If we assume 9 object points, 5 wavelengths, 10 focal shifts, 2 object plane shifts and 2 scans for each image, the total number of spread functions comes to 1,800. Assuming a 5-second scan, this comes to 2.5 hours of scanning for a single lens. In addition to this, several minutes must be allowed for moving the point source, scanner and object plane.

It is obvious that it is not practical to acquire all the data one would like unless one is testing an unusually expensive lens to be used in an important application. For most commercial applications we need to simplify the test procedure.

Practical Short Cuts to Make OTF Measurements Feasible

Fortunately, the following can be done to reduce the amount of data collection and cut down on the time required.

1. The measurements can be made in monochromatic light and compared with the design calculations. As a production control technique, this is probably a feasible technique if some extra measurement is made to check the chromatic aberration. For example, one might measure two wavelengths on axis and compare with design calculations.

2. White light can be used if properly filtered. This is not as easy to do as to talk about. Serious mistakes can be made if this is not done correctly. The problem with this procedure is that it is necessary to depend on the sensitivity curve of photo cells which are not perfectly repeatable from cell to cell and are not too easy to calibrate. If a broad band of wavelengths is used, one must carefully consider the effect of chromatic aberration in any lenses used in the OTF testing system. My experience is that not much attention is paid to this source of an indefinite error in measurements.

The use of a broad band of light does provide much more flux and will appreciably shorten scanning times.

3. Select a minimum number of field points for testing. A minimum of five image points are needed for a given diagonal. There should be at least two diagonals measured. This adds up to nine image points as a minimum number. For production control, however, it might be adequate to consider

using only three points on a diagonal. This, then, brings it down to five field points.

4. Scan each image in a minimum number of directions. Radial and tangential scans are desirable but for production control a single scan in the tangential scan may be adequate. The argument here is that the tangential images tend to move around faster with errors in lens manufacture.

5. The time taken for making a test can be shortened by using multiple sources and scanners with the operations done in parallel instead of series. The ideal set-up consists of several point sources located on a single reference object surface and an equal number of scanners located on a reference image plane. Such a set-up poses many practical engineering problems which are expensive to solve.

6. A practical compromise is to use from one to five point sources mounted on a single straight edge, and from one to five scanners on a parallel straight edge. With several scanners and point sources, the data gathering for all of them can be done simultaneously. A modern mini-computer has such a rapid data collection rate compared to scanning rates that multiplexing can provide for simultaneous collection of the data for each of the scanners.

Design Considerations for MTF Equipment

If one recognizes the ultimate objectives of OTF testing, he comes to the conclusion that the measuring equipment must be an extremely careful design balance between conflicting requirements. The equipment must have versatility, accuracy, a fairly high degree of automation, and reasonable cost. Figures 2 and 3 show some equipment designed to meet these objectives. Many of the principles of design were described in a previous article by the author.[2] In designing this equipment, the following concepts were kept firmly in mind.

A point source of light has many advantages in testing. Some of the testing can be done visually and may not warrant a full OTF test. The point source is close to the fundamental concept of OTF.

The equipment should be capable of using a slit as a source. There are advantages and disadvantages in using a slit. The slit provides more light, but it must have parallel jaws or the slit correction is indeterminate. It is more difficult to uniformly illuminate the slit. Optics used to image the slit must image uniformly along the slit. The slit must be oriented correctly with respect to the scanning slit.

The lens must be mounted solidly in a *V*-block or in a lens plate with a mounting flange which can be accurately positioned in the lens mounting plane.

The scanner should be as simple and dependable as possible. We prefer scanning with a knife edge or a slit. The operator should be able to observe the point or slit image of the lens being tested prior to scanning. The only reason for scanning with a series of slits is to enable the equipment to measure the OTF by analog means. A series of slits in the scanner or analyzer do not

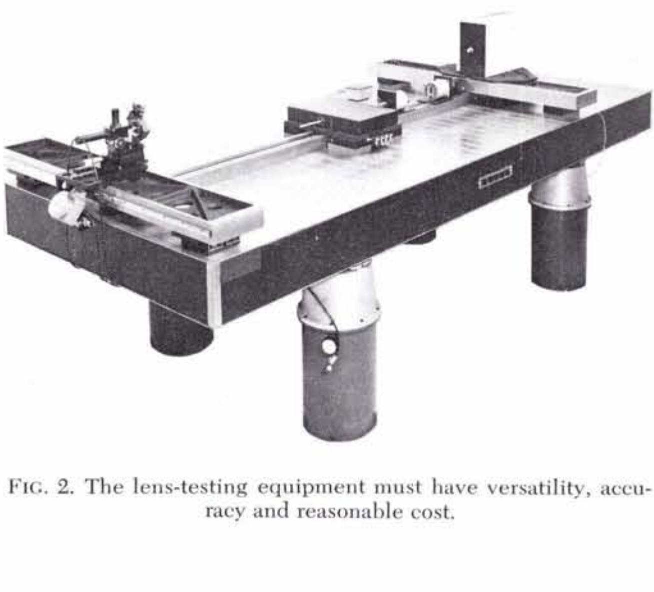

FIG. 2. The lens-testing equipment must have versatility, accuracy and reasonable cost.

FIG. 3. The equipment must have a fairly high degree of automation. A small mini-computer will almost certainly be part of any modern working lens-test equipment.

provide a better signal-to-noise (s/n) ratio. As the OTF testing of lenses requires a computer, there is less justification in resorting to analog methods. The modern mini-computers are so fast and can gather data so rapidly that the bottleneck does not begin to be the computer time required to read the data points. The real bottleneck is speed required to scan with an adequate s/n ratio. By using a single edge for scanning and the computer for computing OTF, one can provide tremendous flexibility. A single scanner can make measurements at frequencies ranging from 1 or 2 cycles/mm to 1000 cycles/mm without changing anything other than the constants in the computer program. The simplicity of a knife edge allows one to change wavelengths easily. Knife-edge scanners work equally well in the UV to the infrared by changing the light source and the detector.

The small mini-computer will almost certainly be part of any modern working lens-test equipment. The speed, memory size and cost of these computers are all moving in the right direction. Through the small mini-computer the optical industry can for once ride along with someone else providing large blocks of technology. We no longer have to make all our own equipment. The mini-computer can compute OTF and at the same time provide the instructions to automate the operation of the equipment. Some of the calculations required are so extensive that the small 8,000-word machines may get indigestion, but there are many options available. The mini-computer can write the information on tape for a larger machine, or it can communicate directly with a large machine.

Clarification of an Optical Myth

One should remember that lenses have been tested for years with extremely modest equipment. Telescope mirrors are tested on a barrel with an automobile tail-light bulb and a razor blade. Hundreds of camera lenses are tested by looking at an image projected on ground glass. Most of the lenses are debugged by visually inspecting the point source image. These methods are simple, cheap, short-cut methods requiring large degrees of skill and judgement on the part of the skilled technician. They provide partial answers to users who have a special requirement. The result is that there are hosts of myths that have grown up about lens testing.

There is also a great deal of reluctance to adopt new methods as long as the old methods work. Today we are faced with the situation that our economic system will not support the skilled technicians of the past. The newer, more thorough testing methods will simply have to come eventually, but no one can expect quick acceptance. One thing that should be avoided, however, is to adopt new procedures by merely retrofitting old devices which were based on the use of the skill of craftsmen. There certainly seems to be a trend in present efforts to measure OTF to base the equipment around the optical benches which were designed for visual inspection and debugging lenses.

There is one particular optical myth that effects thinking in lens testing. This is the *Optical Axis Myth*. Almost any discussion of lens testing will refer to mounting the lens in a bearing so that the optical axis is concentric and coincident with the mechanical axis of the lens bench. The term *optical axis* comes from lens design jargon. It refers to the mathematical line connecting the centers of curvatures of all the rotationally symmetrical spherical surfaces in a theoretical design. The image defects in a centered system have axial symmetry. This is why designers compute only the imagery for a few points on one radius of the field.

In a manufactured lens there is no optical axis as in a paper design. The surfaces are not rotationally spherical, nor are they all centered on a single axis. This is the very reason why people want to test them. They want to know what the effect of these defects, or lack of any optical axis, is going to be on the overall performance of the lens. If one can assume that there is a true optical axis, this means the lens is perfectly centered and made of perfect spheres, then the only problem in testing the lens is to determine if the correction is correct. This can be determined often by visual inspection or, at the most, measuring the OTF at one or two points in the field.

The real problem in lens testing is to determine the performance of the lens where one cannot assume this symmetry and the problem is to find the overall performance of the lens to see if it is in tolerance. The optical axis of the lens then takes on little importance, it represents only one image point among a million. The key questions are what kind of imagery does one get if the lens is mounted on its mounting flange, or how should it be mounted to achieve maximum performance. With this in mind, it is well to redescribe the problem of testing a lens working at finite conjugates as follows:

The geometry of the problem is shown in Figure 4. The object plane, the lens mounting plane and the image plane are adjusted to be parallel to each other. This can be done easily on a lens bench similar to the one shown in Figure 2, by using a collimator and an alignment mirror.

The effective nodal points of the lens cannot be assumed to be located on the line that passes through the center of the lens-mounting plane and perpendicular to the object plane. The effective axis of the lens is not likely to be parallel to the lens bench axis. If the lens is skewed as shown in Figure 4, the image plane will be tilted because of the Scheimpflug condition.

By making focal shift measurements for points in the object plane, it is possible to find the intersection of the best image plane with the YZ-plane. If the lens-mount flange is parallel with the reference image plane, then the best image plane is also known with respect to the mounting flange.

If the lens is tilted in its mount as shown in Figure 4, then the best image plane will show keystone variation of magnification for object points on the object plane. If the data on the lens is gathered on a computer, it is then possible to correct this tilt and provide the description of the plane which has no keystone magnification error. It is not necessary to make adjustments of the lens with respect to the flange mount. By this procedure the intersection of the best image plane and the YZ-plane can be determined and the YZ-component is known. We do not, however, know the coordinate of the point in the X-direction.

The lens may then be turned thru 90° against the lens mounting plane. The lens assumes a new position like the one shown in Figure 4, except the cross section is the XZ-plane. With the same kind of analysis it is possible to find the best focal plane intersection with the XZ-plane, and the XZ-position of the image.

This process may be repeated for several other rotations of the lens. In each instance a best plane of imagery may be found. By combining all the rotations one may find that the

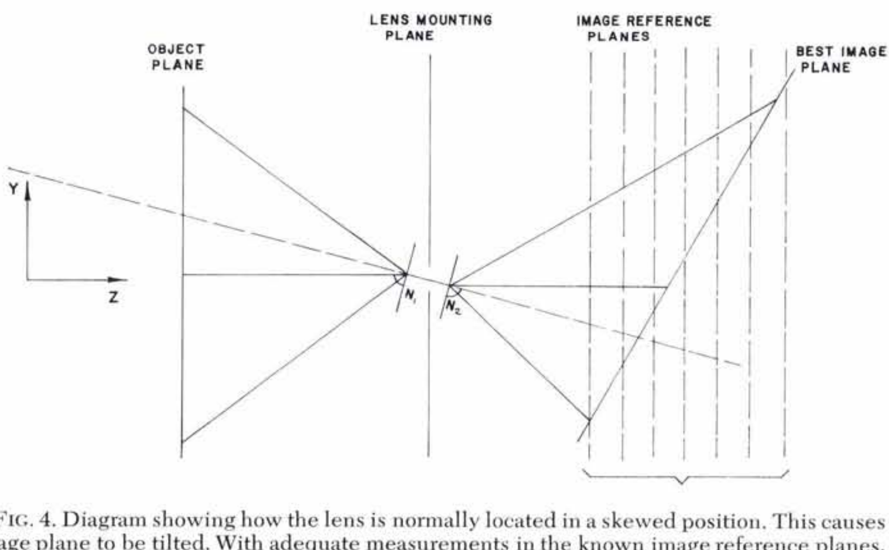

FIG. 4. Diagram showing how the lens is normally located in a skewed position. This causes the image plane to be tilted. With adequate measurements in the known image reference planes, the performance can be evaluated in the best image plane.

best image is not a true plane. If this is the situation, then the computer can find a single plane to provide the maximum FOM for the lens.

There is some tedious analysis that has to be done to do all the above things, but once accounted for, the computer has little trouble faithfully following the rules. It is true that, as the lens is rotated, there may be some slight axial shift of the nodal points, which means that the conjugates are changed. For the small movements encountered it is probably safe to assume that the image performance will not change so that this effect can be accounted for by adjusting all the central images to a single point. In fact, many of the corrections indicated in the above discussion may be unnecessary in most cases, but these are the kind of problems now ignored. By providing for these contingencies in the computer program, one can test with increased confidence that the tests are meaningful.

Summary

OTF concepts are well understood now by workers in the field. There is considerable misunderstanding among the users of optics and even among OTF fans in thinking that OTF is the panecea of lens testing. This simply is not true. The major importance of OTF testing is that we are beginning to calculate and measure the distribution of light in the images. The exact nature of the way we describe the light distribution is of secondary importance and there are no best ways. For the large variety of uses of optics, we need many descriptions.

OTF evaluation is only the beginning of lens testing. It really is *image* testing. We now need to be defining lens quality parameters to describe the performance of the lens over the range of fields and magnifications for which it is to be used. The lenses need to be tested in ways similar to the methods used in lens design so that the designers can receive accurate information on the consequences of their assigned tolerances. To do this takes a large amount of data collection and computer analysis. The quality-control lens-testing bench of the future will surely involve the use of a computer. Without the computer, present day visual eyeballing the lens will remain the mainstay of testing.

References

1. David Dutton, Procedure for Overall Lens Evaluation Using OTF Data, *Appl. Opt.*, 11, 1091 (1972).
2. Robert E. Hopkins, The Remarkable Field of Geometrical Optics, *J.O.S.A.*, 61, 287 (1971).

"Stereoscopy—A More General Theory." (*Continued from page 274*)

the stereomodel as perceived by the observer is a perspective, the scale of which, at any given point, is a function of the depth. This fact, which is unquestionable, makes the comparison between the object space and the model space impossible, unless we consider the perspectivity of the model space negligible due to the small ratio of the anaglyph to the object distance in the case of aerial photography.

Even in this case, the validity of the statement "the vertical exaggeration obtained with a focal-plane lens stereoscope is independent of the stereoscope type" relies absolutely on the "*if* the stereopair separation produces the same convergence angle to the eye." This *if*, though, if far from being true in the general case.

In the development of the theory in question, the three basic variables, i.e., the angles α, ξ and γ, were approximated (Equations 1, 2 and 3) as:

$$\alpha = (p/2)/I$$
$$\xi = (b_T/2)/I$$
$$\gamma = p/h_T.$$

The experiments that support the statement quoted above have shown that "for a constant α/ξ and given γ the observed height to base ratio was always the same."[2]

The first observation is that Equation 1, even if we accept that the approximation is valid, is true *only* for a pyramid located at the mid-point of the axes of the two lenses. Generally though, the range of variation of the angle α is from zero, where the pyramid is under either of the two lenses, to approximately p/I if the pyramid is under the other lens. The respective variation of the angle ξ is much smaller, becoming negligible for a large object distance. Therefore the ratio α/ξ is quite variable *under the same photography and observation conditions,* if we are considering the whole field of view of the stereoscope.

The second observation is that the convergence angle γ can be approximated, roughly always, be Equation 3, but *only for the object space.* The angle γ in Figure 1A has *nothing* to do with angle γ in Figure 1B, and Mr. LaPrade has accepted it.[2] The fact remains that the approximation of γ derived from Figure 1A is used to substitute γ in Equation 5 which refers to the model space, i.e., Figure 1B.

From the moment that γ in Equation 5 or 7 has been substituted by Equation 3, it becomes mathematically possible to come to the conclusion used as subtitle of the article. Because the angle γ of Figures 1B and 2 is function of and *only of* the characteristics of the stereoscope and the observation conditions, whereas γ of Figure 1A as approximated by Equation 3 is a function of and *only of* the flight variables. Thus the stereoscope and observation variables have been substituted by the flight variables (B and H). This actually happens, eventhough not explicitely, if Equations 14, 15 and 16 are developed and the ratio B/H is introduced into the Equation 17.

In support of the statement that "q is independent of the camera focal length" it is claimed that "changing f_c simply changes the photographic scale and both p_c and b_c vary proportionally so α/ξ stays constant." This claim is valid if and *only if* the viewing distance S (Figure 1) is changed proportionally, i.e., if the appropriate (if it exists) stereoscope is used. Unfortunately, this is not possible unless for each aerial camera a special type of stereoscope is designed. Furthermore, this proves that both the principal distance of the camera during exposure and the design characteristics of the stereoscope are significant variables of the model deformations.

It is claimed that "the convergence angle γ . . . depends only on the separation of the photographs and the stereoscope lenses," which is true. A few lines later, though, it is stated that neither of these variables causes a change to the ratio α/ξ, but they "affect the enlargement of the stereomodel." It has been proved in the previous paragraphs that the ratio α/ξ is variable even under the same observation conditions. Dispite this the design constants of the stereoscope, as it has been proved[3], do not have any relation to the scale of the stereomodel, with the exception of the eye-base of its ocular system.

The conclusions to which these statements led contradict well established facts of life. Every photointerpreter has experienced much larger model distortions if he used mirror stereoscopes than if lens stereoscopes were used. This due to the larger viewing distance of the former, which is directly related to the focal length of the stereoscope's ocular system since we are speaking of focal-plane instruments.

Finally the proposition that "$q = C(B/H)$ where C is a constant which varies slightly

(*Concluded on page 302*)