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MULTIFUNCTION TARGETS FOR THE ANALYSIS OF OPTICAL CHARACTERISTICS OF LOW AND HIGH MAGNIFICATION OPTICAL SYSTEMS

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1. Introduction

1.1 A visual test is the most commonly employed test technique for measuring, or calibrating, the performance of lenses and optical systems. The use of a standard test pattern provides quantitative data on the performance of the optical system. There are currently many different tools and products available today that allow for the measurement and calibration of many different parameters relating to the limits of an optical system such as resolution, distortion, field of view, and depth of field. What is lacking, however, is a calibration tool that allows the user to perform all of these measurements on one target. The target presented here is an "all-in-one" multifunction target that allows the user to take accurate measurements of several useful parameters relating to the optics of a microscope or vision system on one target without the need for expensive test equipment. This target can be used for calibration, as well as testing resolution, distortion, and depth of field. Features on this target include variable frequency Ronchi rulings, sets of grids and concentric circles with different line spacing and widths, a microscale, and edge blocks for use with depth of field measurements.

1.2 Two versions of the multifunction calibration target have been designed to meet the needs of different optical systems. The first target is designed to be used with lower magnification systems, specifically 4X-20X objectives. The types of systems that operate in this range could include low-powered microscopes as well as machine vision systems. The second version of the target contains the same basic features as the 4X-20X target does, except that the features on this target are designed to meet the needs of optical systems with higher magnifications. This target is aimed at optical systems that are have higher magnifications and can therefore resolve finer features, specifically objectives ranging from 20X-100X.

2. Target Features

2.1 The decision as to what features would be included on the target and how they would be organized was based on maximizing utility. On each version of the target, there can be found the same basic set of features, with variations in the diameter, feature width, and line width. For both the 4X-20X and the 20X-100X target, there are sets of concentric circles with a crosshair at the center of each set; ten sets of square grids; ronchi ruling line pairs with different spatial frequency ranges on each target; and a linear microscale that runs the length of the target.

2.2 *Concentric Circles:*

2.2.1 The first features on this target are sets of concentric circles found in the upper left-hand corner, five sets on the 4X-20X target, and six sets on the 20X-100X. They are specified by their outer diameter, incremental spacing, as well as line width. Each set of circles has a different OD, so that no matter what objective is being used, the entire field of view can be filled up. For the 4X-20X target, the outer diameters range from 5.0mm to 1.0mm, and on the 20X-100X target, the outer diameters range from 3.0 mm to 1.0mm. They are incrementally spaced out by one of three choices: 0.25mm, 0.1mm, or 0.05mm by diameter. Line widths are varied between 20 microns and 5 microns on the

4X-20X target, and between 10 microns and 2.5 microns on the 20X-100X target. The use for these circles resides mainly in detecting lens aberrations, in particular spherical aberrations.

2.3 *Square grids:*

2.3.1 There are ten sets of square grids on each target. For each target, there are two overall grid widths. On the low-frequency target, widths are either 4.5mm or 2.55mm. For the high-frequency target, widths are either 3.0mm or 2.55mm. The grids on these targets have uses for detecting distortion, as well as being able to use the precise spacing and line widths as a tool for instruments that periodically require recalibration, such as a digital stage on a microscope.

2.4 *Ronchi rulings:*

2.4.1 These targets both contain sets of ronchi ruling line pairs. The units of measure are defined in line pairs per millimeter (LP/mm). A line pair is defined for these targets as a solid chrome line plus its adjacent space. The ranges for the ronchi rulings for each target were decided based upon the typical resolution limits for the objectives specified on the target. The range for the low-frequency target is between 60 LP/mm and 380 LP/mm and the range for the high-frequency target is 240 LP/mm to 600 LP/mm. The incremental steps on the 4X-20X target is 20 (e.g. 60 LP/mm, 80 LP/mm, etc.) and the incremental steps on the 20X-100X target is 20 for the beginning and middle of the target and 10 for the remaining portion.

2.5 *Linear microscale:*

2.5.1 The microscale found on the target is the same on both the low and high frequency versions. It is 68.2 mm long, with 20 divisions/mm, therefore making the divisions 50 microns in width. The microscale has applications as a precise calibration reference to check the accuracy of a movable stage, whether it be a microscope or machine vision system. It can also be used to check the field of view of an instrument in the absence of a digital stage.

2.6 *Edge blocks:*

2.6.1 The edge blocks included with these targets have been specially designed to hold the target at carefully chosen angles to be able to measure the depth of field for a wide variety of objectives. The driving force for having more than one edge block has to do with the working distance of different objectives. Lower powered objectives typically have a long working distance and a greater depth of field, thus requiring an edge block with a greater height. Higher powered objectives, on the other hand, have very short focal distances and a small depth of field. This short focal distance limits the height of the edge block that can be applied to a particular objective. If the block is too high, the objective bezel will hit the target, thereby harming the pattern.

2.6.2 The edge blocks that come with the target are specified in terms of a ratio relating the angle that the block is being held at to a linear distance measured along the x-axis to a corresponding “depth” in the y-axis. Each edge block that comes with the target is labeled with a ratio. This ratio is related to the angle that the edge block is holding the target at. The value of the ratio is calculated by taking the inverse of the tangent of the angle that the target is being held at from the horizontal. The angles for the edge blocks have been carefully selected so that the ratio numbers used with the blocks come out to be integers for ease of calculation. For example, the 10/1 ratio block holds the target at 5.71° from the horizontal. If the tangent of that angle is taken, and the reciprocal is taken of that number, a ratio is created which can be used to relate a linear distance measured in the x-axis to a depth in the y-axis.

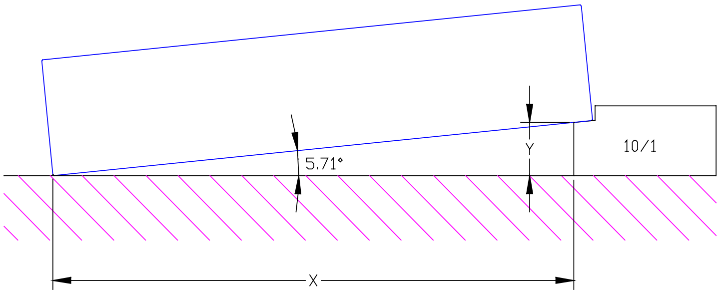


Figure 2.1 – Edge blocks

Each target comes with its own set of edge blocks. The 4X-20X target comes with a 5/1 ratio block, a 10/1 ratio block, and an end support block to prevent the target from sliding off if the stage it is resting on is moved. The 20X-100X target comes with a 20/1, 40/1, and 70/1 ratio block. An end support block is not needed for these blocks as they are much lower in height and there is less of a chance for movement.

3. Applications

3.1 *Lighting:*

3.1.1 These targets can be used with either top or bottom lighting, depending on how the system it is being used on is set up. If top lighting is employed, the light reflects off the chrome pattern, producing white features against a dark background. Conversely, if bottom lighting is used, the reverse will occur and an image of dark features against a clear background will be seen.

3.1.2 No matter which lighting method is used, it is important to have the intensity of the light source adjusted to an optimum level, so that the contrast between the features and the background is very high. This becomes crucial when using the target in a machine vision environment with a camera, where blooming can become a factor.

3.2 *Resolution:*

3.2.1 The ability for an objective or optical system to be able to distinguish fine features from one another is an important characteristic that is frequently tested and used.

A wide range of ronchi ruling line pairs have been included on these targets to help determine the resolution limits of the system.

3.2.2 Before the resolution can be tested, there must first be some criteria as to what constitutes a resolved feature. In the case of the ronchi rulings, the resolving power is defined in terms of the capacity of the instrument to "separate" the images of two adjacent line pairs. When testing for resolution, a separate test should always be performed for both axes in the image plane at 90° angles.

3.2.3 There are two measurements commonly associated with determining the resolving power of an optical system. The first is the maximum measurable resolution, which shows the absolute limits of a lens system in terms of resolving detail. This is found by looking at ronchi rulings with increasing spatial frequencies until the lens or lens system can no longer transfer the fine features anymore and instead of an image of a line pattern, all that is seen is Because very little useful data can be obtained right at the limit of an optical systems' resolution, it is helpful to define another limit for the resolution of a system, one that gives a realistic workable limit in terms of resolution. This limit is the maximum resolution for best acuity. It can be expressed as the highest spatial frequency that can be imaged and still maintain good edge acuity, or black/white transition.

3.3 *Modulation:*

3.3.1 Most lenses including the human lens are not perfect optical systems. As a result, when visual stimuli are passed through them, they undergo a certain degree of degradation. Remember that in a square wave grating, or ronchi ruling, there were dark bars and light bars. The amount of light that is coming from each can then be measured using a captured image from a machine vision system. The maximum amount of light will come from the light and the minimum from the dark bars. If the light is measured in terms of luminance (L) we can define modulation according to Equation (1):

$$\mathrm{mod}\,ulation = \frac{(L_{\max} - L_{\min})}{(L_{\max} + L_{\min})} \tag{1}$$

where L_{max} is the maximum luminance of the grating and L_{min} is the minimum luminance. (Jenkins, White 366) When modulation is defined in terms of light it is frequently referred to as Michelson contrast. Taking the ratio of the illumination from the light and dark bars is measuring contrast.

3.3.2 Suppose that you have a square wave grating of a specific frequency (v) and modulation (contrast) and this stimulus is passed through a lens. The modulation of the resulting image can now be measured.

3.3.3 The modulation transfer function (MTF) is defined as the modulation, M_i, of the image divided by the modulation of the stimulus (the object), M_o, as shown in Equation (2),

$$\mathrm{MTF}(v) = \mathrm{M}_i / \mathrm{M}_0 \tag{2}$$

3.3.4 By sampling enough spatial frequencies over regular intervals on the ronchi ruling and plotting them vs. their respective modulations, a good approximation of one aspect of the lens' performance characteristics can be obtained. A sample graph of one possible lens can be seen below in Figure 3.1.

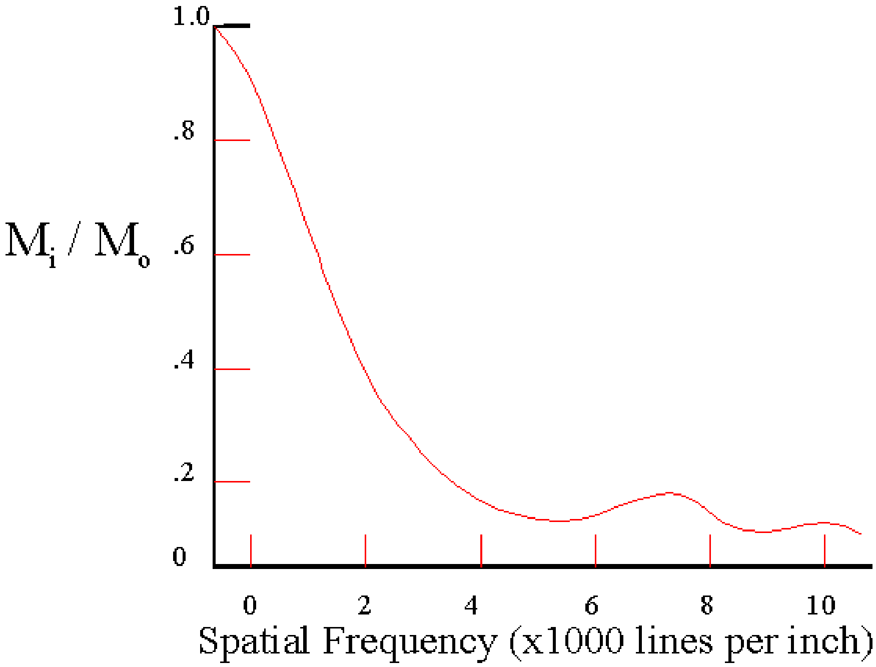


Figure 3.1 – Modulation Transfer Function

3.3.5 It can quickly be discerned that the MTF of a lens or lens system contains more information than just the point where resolution falls off. From a graph like this, it can be determined how fast the resolution degrades. Two different lenses might reach zero modulation at the same spatial frequency, but they might have two completely different graphs.

3.4 *Distortion and Lens aberrations:*

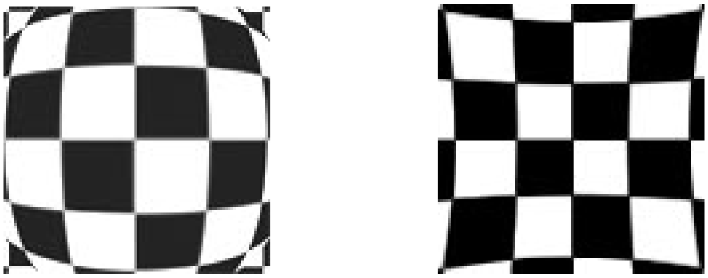
3.4.1 There are five basic aberrations that are responsible for a lack of sharpness in an image. These are called Seidal aberrations. Of the five Seidal aberrations, three (namely spherical, coma, and astigmatism) are responsible for lack of sharpness of the image. The other two (namely curvature of field and distortion), are related to the position and form of the image, without any actual loss of information.

3.4.2 Utilizing the square grids and concentric circles found on the multifunction targets, it is possible to detect the presence of three out of the five Seidal aberrations, which are spherical aberration, astigmatism, and distortion.

3.4.3 Spherical aberration is a lens defect in which image forming rays passing through the outer zones of the lens focus at a distance from the principal plane, different from that of the rays passing through the center of the lens. Depending on the cube of ρ, the ray distance off axis, gives a point focus for the paraxial rays; the extra wave curvature for large values of ρ directs rays to cut the axis in points in front of or behind the point focus. Those rays form a halo around the focal point. This can also be detected using concentric circles found on both versions of the multifunction target. If the center of the equally spaced circles is lined up with the optical axis, any spherical aberrations will show up as a deviation in the spacing between consecutive circles.

3.4.4 Astigmatism is a result of cylindrical wavefront aberration, which increases as the square of the distance off axis and the square of the aperture ρ. The focus shown consists of two concentrations of rays known as the focal lines, with a blurred circular region representing the best approximation to a point focus. By positioning the concentric circles at various points within the field of view, astigmatism will show up as an elongation or stretching of the circles into ellipses. This will probably be most noticeable with the smallest of the circles.

3.4.5 Distortion represents an angular deviation of the wavefront, increasing as the cube of the distance away from the axis. This spreads or contracts the image, destroying the linear relation between dimensions in object and image. When viewing square grids possessing this distortion through a lens or lens system, it shows up as a pincushioning or barreling effect. Pincushioning occurs when there is an increase in magnification towards the edge of the field. Barreling occurs when there is a decrease in magnification towards the edge of the field. (Jenkins, White 152) An example of each can be seen below in Figure 3.2.



(a) Barreling (b) Pincushioning

Figure 3.2 – Barreling and Pincushioning

3.5 *Depth of Field:*

3.5.1 Depth of field is the range of distances in the object space which will displace the final image over a range s. This is not to be confused with depth of focus, which is the difference in focal position which can be tolerated without sensible degradation of the image quality. Obviously, its value depends upon what is considered to be "sensible degradation", and will vary with circumstances.

3.5.2 As discussed earlier in the explanation of the edge blocks, the primary reason for having many different heights of edge blocks have to do with the objectives being used to view the target. For lower powered objectives, which typically have a large depth of field and long working distances, it is necessary to use higher edge blocks which will hold the target at a steeper angle

3.5.3 The edge blocks included with the multi-function target package are designed specifically for use with depth of field measurements. What they allow the user to do is create depth based off of a flat target. When the target is propped up on one of the edge blocks, a linear "in focus" distance can be measured in the X-Y plane. This distance can then be translated into a vertical "depth" by dividing it by the ratio number of the edge block being used, as shown in Figure 3.3.

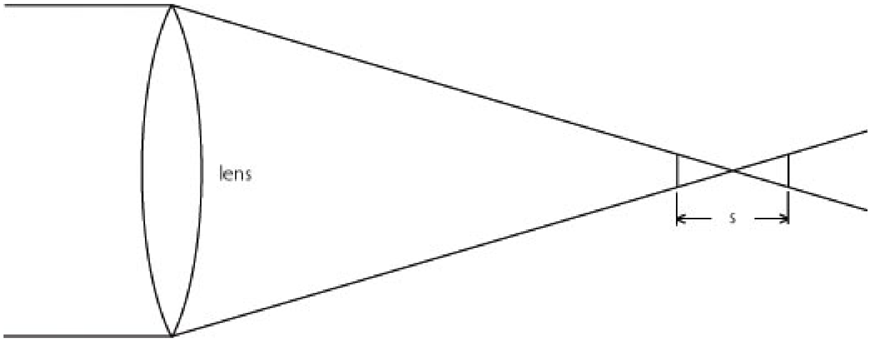


Figure 3.3 – Depth of Field illustraton

3.5.4 Depth of Field is found by first setting the target on the edge block that allows the user to focus on the target without the objective bezel touching the glass. Focusing on the edge of the ronchi ruling that gives the maximum resolution for best acuity (see 3.2.3), measure the linear "in focus" distance in the image plane. Dividing this distance by the ratio of the edge block being used will give either the near or the far field. If the pattern is going out of focus as the target is getting closer to the objective, that distance, L_N, corresponds to the near field. If the objective is getting further away, the distance for the far field, L_F, is being measured. The total depth of field is the combination of the near and far field values.

$$nearfield = \frac{L_N}{B} \tag{3}$$

$$farfield = \frac{L_F}{B} \tag{4}$$

$$DOF = near\ field + far\ field \tag{5}$$

3.5.5 In the absence of a digital stage to measure the linear "in focus" distance, the linear microscale located at the bottom of the target can be used in its place. Once the target is on the appropriate edge block and focused on the edge of the ronchi ruling, simply move the stage in the direction parallel to the ronchi ruling lines and note the corresponding position on the microscale, then return to the previous coordinates on the ronchi ruling. After moving the stage down to the end of the "in focus" distance, repeat the steps to check the current location on the microscale and then subtract the two values from each other.

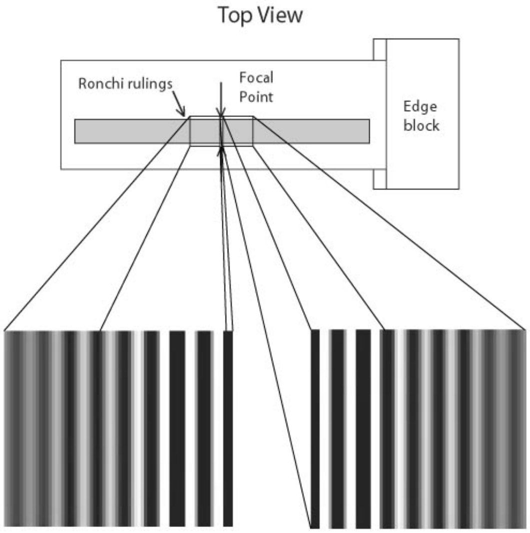


Figure 3.4 – Comparison of the near and far fields

3.5.5 When determining depth of field, it is also important to consider the lighting scheme being employed. Because the target is being held at an angle, any collimated light source used to illuminate the target, such as through-the-lens lighting, will simply reflect off the target and away from the lens, and no image will be seen. For the best results when the target is on edge blocks, bottom lighting should always be used.

3.6 *Field of View:*

3.6.1 There are two possible methods for calculating the field of view of an optical system using either of the multifunction targets. The first method requires that a digital X-Y stage be present. The second method can also be used in the event that a digital stage is not present.

3.6.2 Method using digital stage and crosshair reticle

3.6.2.1 Using a low frequency ronchi ruling on the target, first orient the target so that the rulings are aligned vertically with the y-axis of the stage. Position the target so the right edge of the field of view is in line with the far right edge of the

3.7 *Calibration:*

3.7.1 There are multiple features related to these targets that lend themselves to calibration of an optical instrument, whether it is a high-powered precision microscope, or a machine vision system with relatively low magnification.

3.7.2 First and foremost is the inclusion of a linear microscale that runs along the bottom of the target. This is useful for checking the field of view, as well as the accuracy of the stage it is sitting on, whether it is digital or mechanical.

3.7.3 The square grids are a reliable calibration tool as well, giving a regular, repeated pattern and line width with which to calibrate against.

3.7.4 It is also possible to calibrate the z-axis, or the axis that is perpendicular to the stage, by using the edge blocks used for depth of field calculations. This is done by focusing on the edge of a ronchi ruling, and then moving a known distance across the ronchi ruling. From this point, move the focus so that the area being imaged comes into view. Then take the known distance that the stage was moved and divide it by the value of the ratio block being used. The resulting number is the actual distance moved in the z-axis.

4. Keywords

4.1 calibration; microscopes; machine vision; depth of field, resolution; distortion; field of view; modulation, modulation transfer function (MTF); grids; concentric circles; ronchi rulings; microscale

5. Conclusion

5.1 There is a continual need for products that allow for the calibration of precision optical instruments used in a wide variety of industries, ranging from high precision microscopes to machine vision systems. Although there are currently a wide variety of products that can be used for measurement and calibration of one of these parameters, until now, there has not yet been a calibration target that can meet the majority of these needs. The multifunction target has been designed to be versatile to allow it to be used with a wide range of optical systems. It includes the features most commonly used for calibration: ronchi rulings for testing resolving power, concentric circles and square grids for detecting distortion, a linear microscale to use as a measurement standard, and edge blocks which allow a flat target to be used to measure depth of field. Two separate versions of the target have been designed to cover a majority of the range of objectives used with optical systems. The low frequency target is specified for use with 4X-20X objectives. This range is particularly suited for machine vision systems, which typically work in this range, whereas the high frequency target is designed for use with 20X-100X objectives, which is most often the objective range used by high-powered microscopes. This target is unique in that it can establish itself as the first true "multifunction" calibration target that can be used test optical systems.

6. Reference Material

Smith, Warren J. "Modern Optical Engineering." 3rd ed. McGraw-Hill, 2000.

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