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TECHNICAL PAPER

An on-line optical bench tester machine for evaluating lens quality

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Abstract This study is dedicated to develop an on-line automatic optical bench tester (OBT) machine for evaluating the image quality of a camera lens that is used in a lens module of a cell phone. This tester is not only suitable for conventional solid lens, but also applicable to the developing cutting-edge tunable liquid crystal lens. The testing is accomplished via a specially-designed OBT machine, which is able to automatically move the test lens based on feedback images in the optical system in the OBT to the axial position that leads to best imaging quality and also successfully measure its focus length. In the designed OBT, a commercial inspection chart is employed, along with an automatic lens-feeding machine for a quick estimate on the best possible focusing quality, which is evaluated by the well-known modulation transfer function (MTF). For actuating the feeding machine, an algorithm, assisted by the feedback MTFs, is proposed to move the test lens to the particular position that renders the best quality. In this way, the focus length—effective focal length (EFL)—of the test lens can be obtained. The proposed algorithm in fact needs much less time of actuation than a traditional tester to obtain EFL of the test lens. The designed and constructed tester is capable of measuring varied optical performance indices for the next-generation tunable lens, like liquid crystal lens.

1 The optical bench tester

This study is dedicated to develop an on-line automatic optical bench tester (OBT) machine for measuring the effective focus lengths (EFL) of test lenses and also evaluating the image quality of a manufactured lens. The OBT developed in this study as schematically shown in Fig. 1 is aimed to measure the modulation transfer function (MTF) and other lens characteristics with simple, fast operations and low-cost apparatus. In this machine, a CCD is used as an imaging sensor along with an easy-to-operate computer interface in a personal computer to conduct required computation and then draw conclusion on lens evaluation. The CCD is placed on the image position to sense the object image through by the lens to test. Figure 2 offers a photo on the developed OBT machine in laboratory.

As for the case using a commercial inspection chart, a chart with interested varied line pair intensities are fabricated and placed between the light source and CCD camera (Toshiba data book 1992). The position of the lens is adjusted based on feedback image quality automatically by the designed feeding mechanism, in order to find the best focusing quality in terms of feedbacked image quality. With the lens staged at the position and giving best MTF (Chang et al. 2007; Kapany et al. 1968), the image of different patterns with varied line pair intensities are analyzed to obtain associated MTF values (Hwang and Wan 2008). In this way, the MTFs versus varied line pairs can be obtained and plotted for assessing the focusing quality of a manufactured solid or tunable lens (Estribeau and Magnan 2004a, b). Users of this OBT needs only to place the lens in this tester machine—do not need to adjust manually for the best test lens position.

This paper is organized as follows. The structure and components of the OBT is briefed in this section. Methodologies, theories and working principles behind the OBT are given in Sect. 2. The operations of the OBT are elaborated in Sect. 4 while experiments are conducted and stated in Sect. 4. Finally, conclusions are drawn in Sect. 5.

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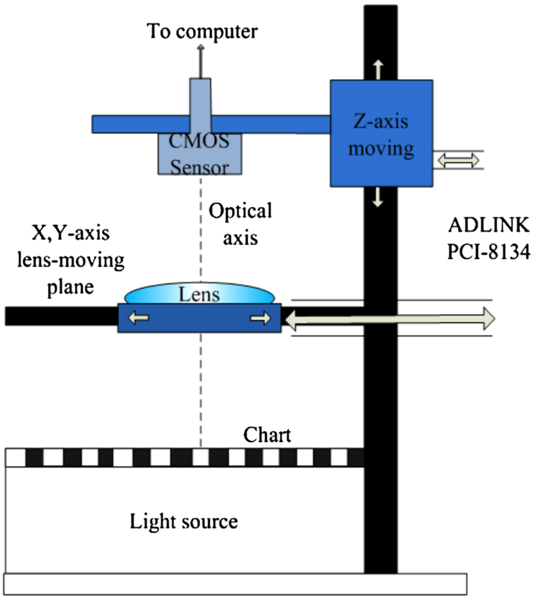


Fig. 1 Schematic of the designed optical lens test bench machine

Fig. 2 The outlook of the realized optical lens test bench machine

2 Methodology

In the OBT developed by this study, a CCD camera is used to capture images though the test lenses. Then, an algorithm used to compute MTF values is developed to analyze images for assessing image quality and then reveal lens focusing capability.

2.1 Computing MTF

Patterns of line pairs in varied spatial frequencies are designed, fabricated and incorporated into a single chart realized by a plastic sheet for testing lens quality in the OBT which is designed and proposed by this study. The chart is shown in Fig. 3, where four different spatial frequencies for line pairs are present. In this way, four different MTFs can be obtained in later testings. Figure 4 displays an imaging example of the line-pair pattern sheet through the OBT. The MTF values over four different regions with varied spatial frequencies for line pairs are calculated evaluate lens quality. Recognizing in this image that black lines own the highest intensities while white lines own the lowest intensities, the modulation for a given image can be calculated by

$$Modulation = \frac{I\mathrm{max} - I\mathrm{min}}{I\mathrm{max} + I\mathrm{min}} \tag{1}$$

where $I_{\max}$ is the maximum intensity of the chart or the image while the $I_{\min}$ is the minimum intensity. Based on the above Eq. (1), the original modulation for the sample chart ($\mathrm{Modulation}_{\mathrm{Object}}$) and that for the image ($Modulation_{\mathrm{Image}}$) can both be calculated. Then the normalized MTF value (Chang and Yao 2005) can be obtained by

$$MTF = \frac{Modulation_{\mathrm{Image}}}{Modulation_{\mathrm{Object}}} \times 100\,\% \tag{2}$$

Note from the above Eq. (2) that the image modulation is always smaller than object modulation; therefore, the value of MTF is always between 0 and 1 (100 %). This MTF value can be easily calculated using a computer algorithm, which is later incorporated into part of the OBT system. It should be noted that the MTF value changes not only due to different lenses but also varied spatial frequencies of line pairs in the pattern sheet. In other words the MTF is a function of spatial frequency, generally expressed as MTF(*f*). As *f* increases, MTF usually decreases for a given solid practical lens (Kapany et al. 1968). In practice, also for the OBT system proposed by this study, the grey levels of the images captured by the camera for black and white stripes are usually off 0 and 255 slightly in a system of total 256 grey levels due to the imperfections involved in the optical transmission of the OBT lens system. Therefore, the modulation calculated by Eq. (1) for images, $Modulation_{\mathrm{image}}$, varies from 0 to 255 even for the locations where there are clearly black and white strips in the CCD camera images. To improve this, the normalization with respect to the MTF

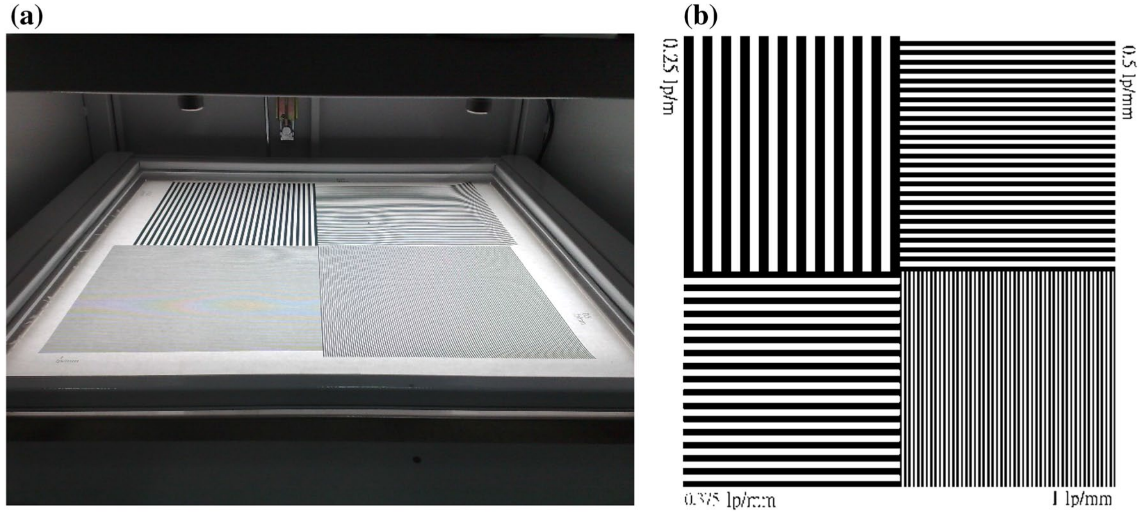


Fig. 3 The test sample chart with four divided regions in varied-density *line pairs*: **a** a photo and **b** the original design layout

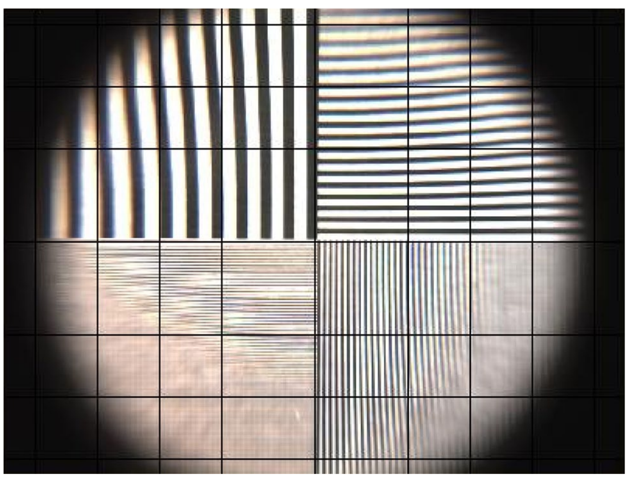


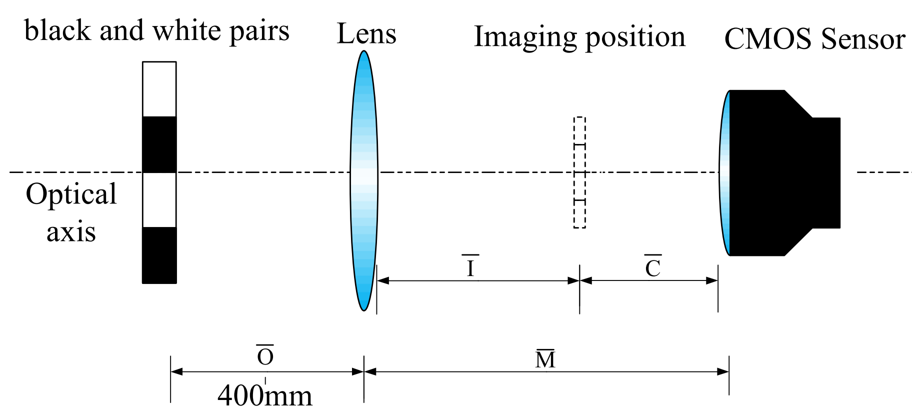
Fig. 4 The imaged photo on the test sample chart with four *line* charts in varied densities of *lines*

of the OBT itself (without test lens placed) was recommended by Eq. (2), the newly-calculated $Modulation_{\mathrm{image}}$, which is able to assess the test lens quality with MTF values ranging from 0 to 100 %. The MTF value of 100 % indicate a perfect lens imaging quality, while zero does the worst lens quality, basically no imaging effects at all offered by the test lens.

2.2 Lens vehicle with automatic calibration

A baseline schematic of the optical system as shown in Fig. 5 is designed and installed in the OBT proposed by this study, which consists of a CMOS camera, a lens moving along the optical axis and the object, a black-and-white line-pair sheet. This optical system aims to move the test lenses to the axial position that leads to the best imaging quality based on the MTF values of the images feedbacked

Fig. 5 Illustration of measuring the focal length of a test lens



from the imaging CCD camera. As illustrated by Fig. 6, the CCD images always have lower MTF values than the original line-pair sheet. The calculated MTF values reflect well the degree of imaging quality offered by the designed optical system. Equations (1, 2) are employed to calculate MTF values based on the images captured from the CCD camera.

2.3 Calculating focusing lengths based on Lens Maker's formula and CMOS images

In the OBT optical system, associated basic optics follows the known Lens Maker's formula that describes the correlation between object distance $\overline{O}$, image distance $\overline{I}$ and lens focal f, yielding

$$\frac{1}{O}+\frac{1}{I}=\frac{1}{f}. \tag{3}$$

The image was first captured with lens moved to different positions, then the captured CMOS camera images are processed by the MTF computation algorithm proposed in Eqs. (1, 2) to find the particular position that leads to the images with the maximum MTF value, i.e., resulting in the best images in the CMOS camera. With the lens moved to this position by an actuator installed in this OBT and images from the CMOS camera, this optical OBT lens system is considered well focused, and the focus length of the lens can be calculated based on known O and I in Eq. (3).

It is important to note at this point that the CMOS sensor also owns its internal lens group (Greig et al. 2007), thus Eq. (3) has to be revised to render the correct focal length of the test lens. To this end, the internal optical imaging system of the CMOS camera is explored. Having known the lens properties of the internal lens group of the CMOS camera, one can find the imaging plane in front of the CMOS sensor, as denoted in Fig. 5, in a distance of $\overline{C}$ in front of the CMOS sensor (Lerman 1968; Smith 1990). Base on this fact, the imaging distance is then revised from $\overline{M}$ to $\overline{I}$, which can be actually obtained by $\overline{I}=\overline{M}-\overline{C}$. Finally, this revised imaging distance of $\overline{I}$ is substituted into Eq. (3) for calculating the focusing length of the test lens.

3 Operations of OBT

To achieve evaluations on lens quality, the test lens in the optical system of the OBT designed by this study, as schematically shown in Fig. 5, is actuated to move along the optical axis to search or the best position that leads to the

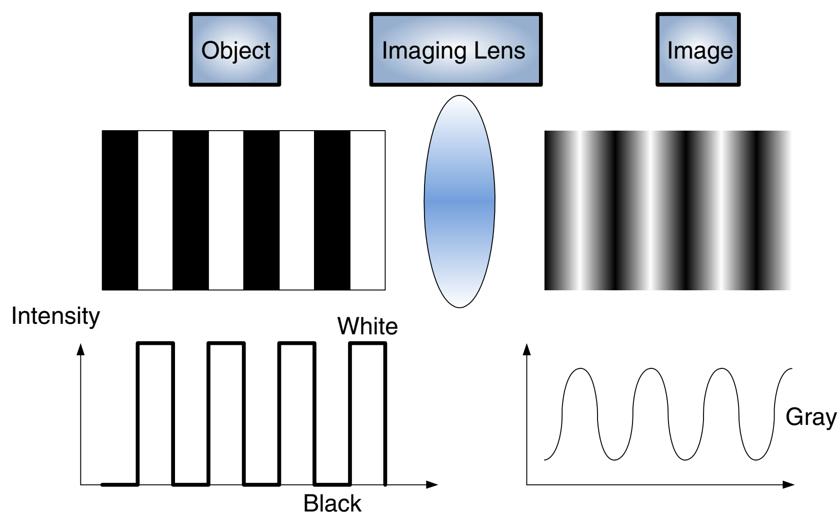


Fig. 6 Illustration of the MTF algorithm

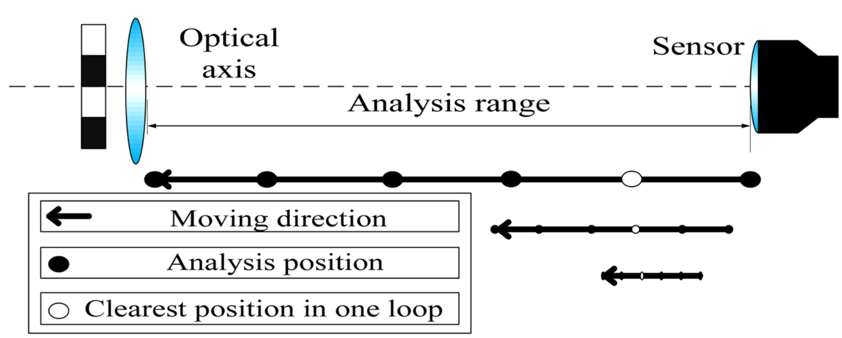


Fig. 7 The designed actuation process for the sensor to achieve the best focused images

best image quality, such that the lens characteristics and quality can be distilled and evaluated, respectively. Figure 7 illustrates the designed actuation process on the test lens to achieve best focusing images. As illustrated, the test lens are moved over the entire range in courser steps (in fact 10 steps) for the first run, while approaching subsequently the

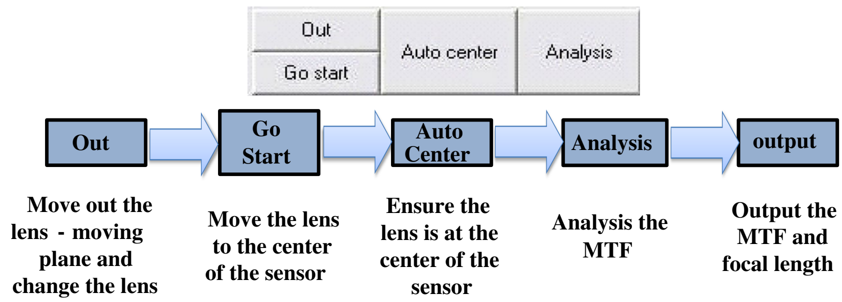


Fig. 8 The testing procedure adopted by the designed optical lens bench tester

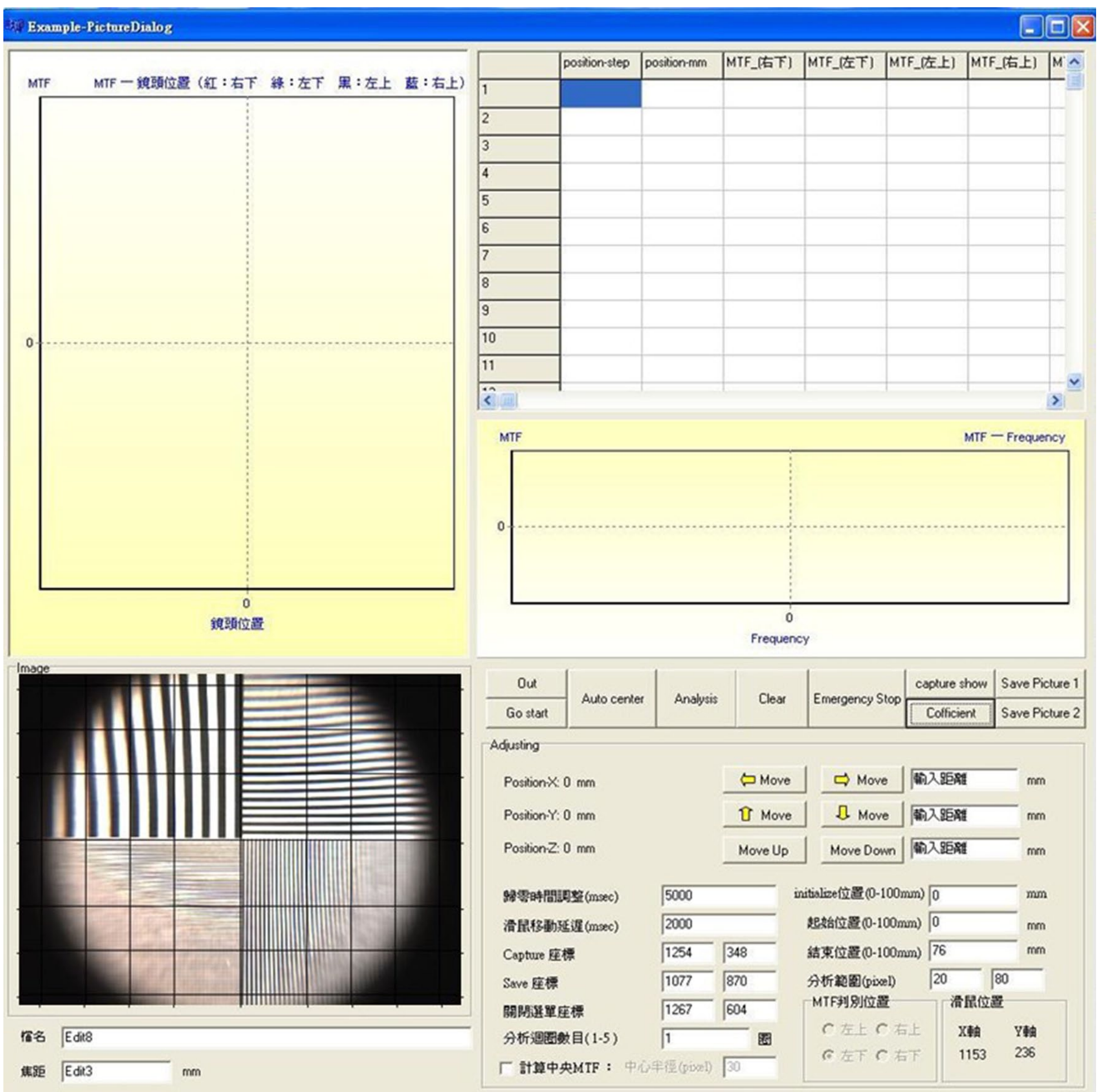


Fig. 9 The computer user interface

position with the best image resulted by the known binary step search. With the optical system and actuation strategy well developed, the sensed image data is captured by a personal computer in real time and then processed by computer software to calculate the following optical characteristics for the test lens: (1) MTF, (2) distortion, (3) optical axis misalignment, (4) magnification, (5) relative F number.

The operation of the developed OBT is illustrated by Fig. 8, where the block diagram is used to elaborate the operation and also subsequent calculations. In this operation, the first step is to place and fine-position the center of the test lens via an actuating X–Y moving lens holder and based on the feedback images from the CCD camera. In this way, the test lens can be aligned with the center of the sensor camera on the optical axis; then, calculating varied performance indices regarding lens quality. Note that the aforementioned lens-centering is considered necessary since the lens center may be slightly off the optical axis during the aforementioned process of axial actuation. The test lens is next moved along the optical axis following the actuation strategy stated, as the image quality is evaluated at each step based on the MTF calculated by

$$MTF_{\text{mea}} = MTF_{\text{lens}} \times MTF_{\text{others}} \tag{4}$$

where MTF_{mea} denotes measured by the OBT; MTF_{lens} does the actual MTF of the test lens which is used to

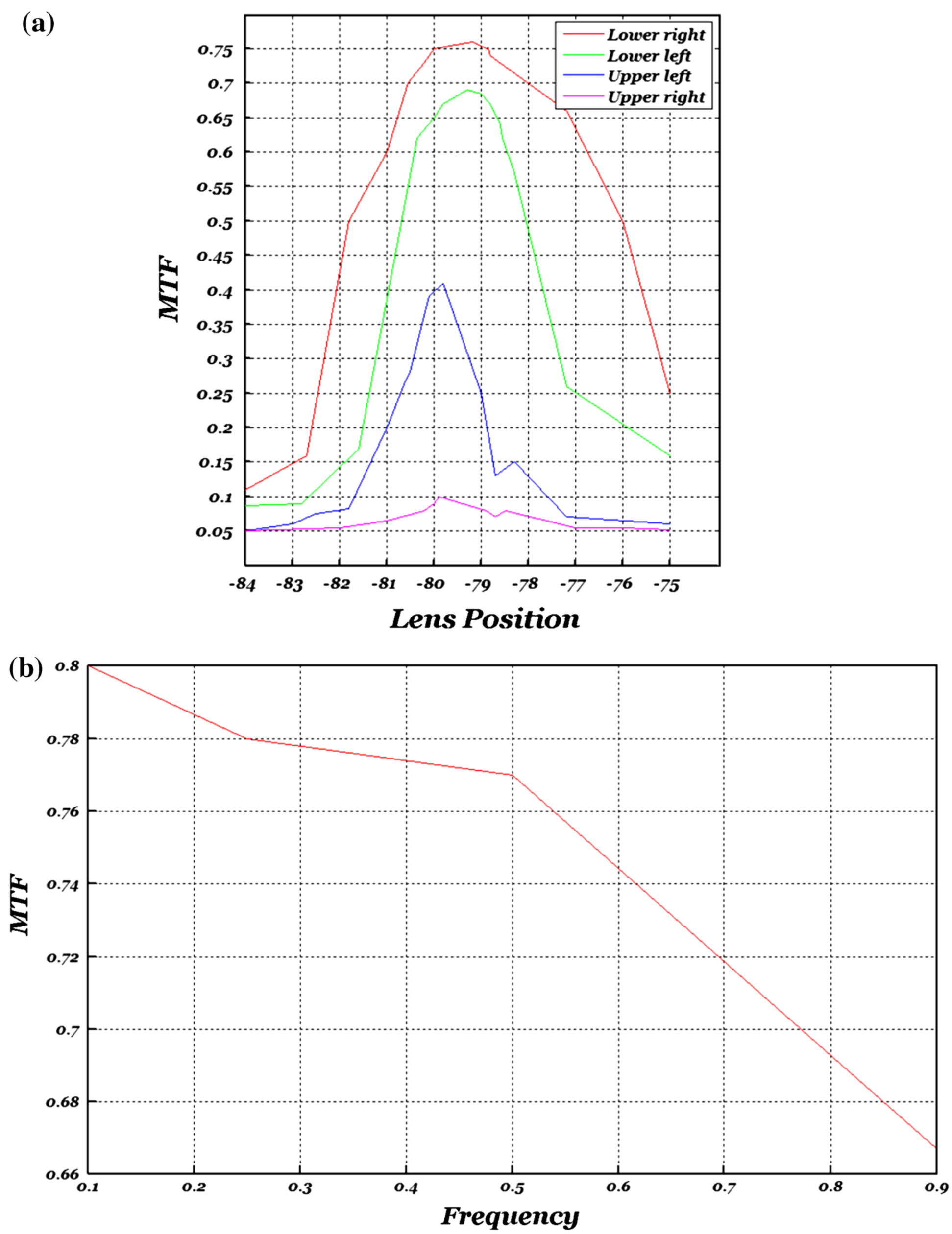


Fig. 10 **a** MTF versus position and **b** MTF versus frequency for lens A

evaluate lens quality; MTF_{others} is the integrated noise in MTF that is resulted from the other optical components in the employed optical system as shown in Fig. 1, including those from the peripheral components of the light source and the CCD, etc. To eliminate MTF_{others} in the measured MTF_{mea}, the value of MTF_{others} has to be identified, which can be accomplished by pre-calibrating the OBT by a sample lens with known and validated MTF. Note that Eq. (4) is in fact a mirror reflection of theoretical Eq. (2). MTF_{mea} corresponds to $Modulation_{image}$; MTF_{others} corresponds to $Modulation_{obect}$; MTF_{lens} is exactly the MTF defined by Eq. (2). With MTF evaluated at each step of lens actuation using Eq. (4), the test lens is then able to be moved along the optical back and forth following the aforementioned binary search method until the camera image are ensured reaching the maximum MTF values. Once the camera

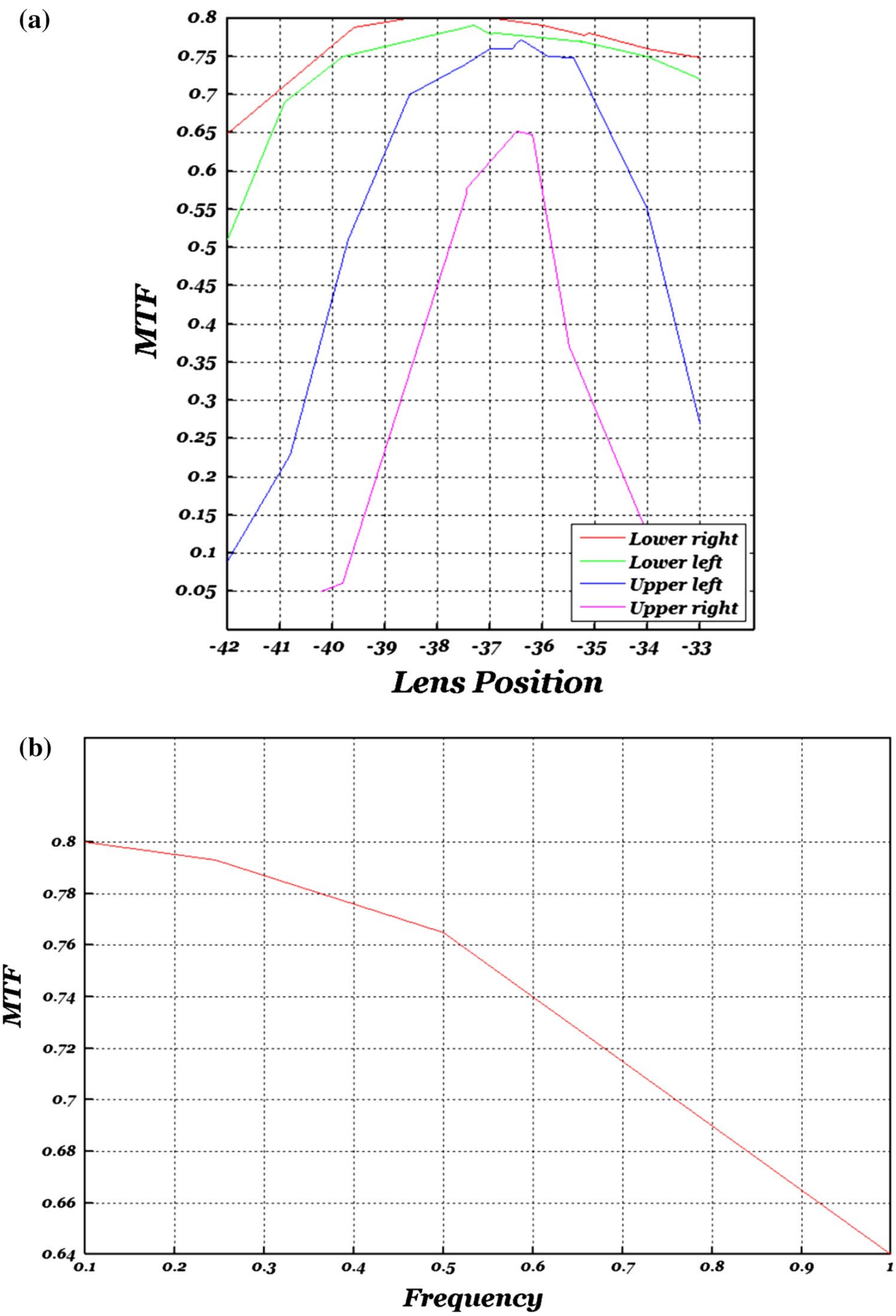


Fig. 11 **a** MTF versus position and **b** MTF versus frequency for lens B

image is ensured reaching the best resolution based on captured images and calculated MTFs, the optical system of the OBT are considered focused, then the focusing length, MTF values, F number, and filed of view (FOV), etc., are obtained and stored further lens quality evaluation.

A system interface for easy user operations is constructed and shown in Fig. 9. This system has been used by lens manufacturers and being proven a very useful instrument for quality check of the production lens. The information displayed by this interface includes realistic images on the line pair chart, extract MTFs and associated plots. The users only need to press one button of the computer interface to command the OBT to perform lens actuation and MFT computation. This system performs the measurement automatically and creates a data bank which contains the measurement result in an excel file. The result is then displayed on the computer screen. The whole operation can be finished in 10 s.

4 Experimental results

Two different unknown lenses, denoted as A and B, are taken as examples to validate the testing performance of the proposed and well-developed optical lens test machine. Experimental results are shown in Figs. 10 and 11, where the MTF values computed based on experimental data by the developed test bench machine are presented versus lens position and frequency of the lines pairs. The line pair chart as shown in Fig. 3 is utilized herein for testing the lens quality. Subfigures (a) presents the MTF values as the test lens is placed and moved to different relative axial positions to the sensor camera. The maximum MTFs over all axial positions for different line pair patterns in varied densities are extracted to construct subfigures (b), where they are integrated into a single plot of TF versus line pair frequency for lens quality evaluation. Note that among all MTF curves in subfigure (a), the line pair pattern in the lower right region of the sample as given in Fig. 3 results in the largest maximum MTF over all lens positions. This is simply due to the fact that the lower right line pair pattern as shown in Fig. 3 is in highest density of line pairs. On the other hand, the lens position corresponding to maximum the MTF can be identified as the EFL of the test lens. Also, it is seen from subfigures (b) that lens A and B result in close MTF values at high frequencies, while lens B performs better than A in the regions with the frequency close to 0.2. It can be concluded at this point that the lens qualities are successfully presented in terms of MTF values for different frequencies; furthermore, validating the favorable performance of the proposed lens quality test bench machine.

5 Conclusive remarks

An on-line lens-quality test machine is successfully developed and validated in this study. The machine is designed to measure and evaluate imaging quality of test lenses based on calculated MTF values. To test the performance of the developed machine, an inspection line-pair chart in four different densities, a designed operation and lens-actuation procedure based on image feedback from capture camera are designed and employed to the aforementioned ends. The execution of the testing proves that the test machine is capable of offering accurate estimates on the EFL of the test lens, favorable quality evaluation based on obtained MTF values at varied line pair frequencies. A computer interface is also successfully constructed for an easy operation to users. The entire testing operation can be completed within a short period of time as 10 s. In the future, the line pair chart can be revised to include more patterns cover a broader range of line pair densities, while the actuation mechanism and strategy are also needed to be further excelled to reach faster and more accurate operations. With this test machine well developed, some next-generation lenses with EFLs possibly tuned in an on-line fashion by external voltages, like liquid crystal lenses (Chao et al. 2012) can then be tested and evaluated by this machine in an on-line fashion.

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