Aberration compensation using a spatial light modulator LCD

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Abstract. The dynamic correction of aberrations introduced in optical systems have been a widely discussed topic in the past 10 years. Adaptive optics is the most important developed field where the Shack-Hartmann sensors and deformable mirrors are used for the measurement and correction of wavefronts. In this paper, an interferometric set-up which uses a Spatial Light Modulator (SLM) as an active element is proposed. Using this SLM a procedure for the compensation of all phase aberrations present in the experimental setup is shown.

1. Introduction

Adaptive optics systems are used nowadays in astronomy and physiological optics for measurement and correction of wavefronts. The Shack-Hartmann sensors are typically used for wavefront detection and measurement while deformable mirrors or Liquid Crystal Devices (LCDs) are used as correction systems; moreover, transmission liquid crystal devices have been used to measure and correct optical aberrations in configurations such as the Mach-Zender [1], Twyman-Green [2] and Young [3] interferometers.

This work presents a method to measure and compensate the wavefront alterations using a reflective Spatial Light Modulator (SLM) in a Michelson interferometer. The wavefront distortion in our setup is due primarily to the curvature of the SLM surface. Nevertheless, the proposed method corrects wavefront deformation no matter its origin. The presented method measures phase distortion maps from interferograms recorded on a CMOS camera by a four-step phase-shifting algorithm using the SLM as a phase-shifter. The phase correction is calculated from this phase distortion map, and the proper gray scale values to be displayed in the SLM are obtained using a calibration curve. The final result is a grayscale phase distribution on the SLM that corrects system phase alterations.

2. Experimental Setup

The experimental employed is a Michelson interferometer that replaces one of its mirrors by a HoloEye LC-R-2500 SLM as shown in Figure 1. This last component has an effective area of 14.6 mm × 9.5 mm and is composed by square pixels of 19 \( \mu \)m in length. The light source employed was a polarized 442 nm He-Ar laser. Moreover, a half-wave retarder plate was placed in front of the laser to rotate the beam polarization and control the beam intensity after crossing the polarizer (P). The configuration polarizer (P)/analyzer (A) allowed the SLM works in phase-only mode. The collimated light source was divided by a non-polarizer beam-splitter cube, and...
a L1-L2 lens system formed the image of the entire SLM area on the CMOS sensor. This sensor has an effective area of $6.66 \text{ mm} \times 5.32 \text{ mm}$ and is composed of square pixels of $5.2 \mu \text{m}$ in length.

3. Method

In order to start applying the compensation method, it is necessary to find out the proper polarizer/analyzer configuration for the SLM at 442 nm. The characterization curves were found using the method developed in [4]. This method requires the record of two interferograms on the CMOS camera. An image of a tilted plane with 256 gray levels is displayed on the SLM while the first recording was performed, and a constant gray level image is shown on the SLM to record the second one. The phase distribution for the two interferograms is found using a standard Fourier transform fringe analysis technique. Afterwards, the two phase maps are subtracted and the SLM phase modulation is found by relating the resulting phase map to the tilted grayscale image used. This method suggest covering the M2 mirror and recording these same two images in order to characterize the SLM amplitude mode. The ratio between the two images gives the amplitude response of the SLM. By applying the described method, the best phase configuration finally used had a polarizer rotated $5^\circ$ clockwise and an analyzer rotated $7.5^\circ$ counter-clockwise. The phase and amplitude characterization curves for this final polarizer/analyzer configuration are shown in Figure 2.

The method used for the compensation of the phase alterations in the optical system is based on the digital calculation of the compensatory phase to be displayed on the SLM. This compensatory phase is obtained from the measured phase in an interferogram recorded on the CMOS. However, the size and resolution differences between the CMOS and SLM, the alignment errors between these two elements and the influence of the imaging system, lead to mismatch between the CMOS and SLM coordinates. To solve this issue, an adequate coordinate transformation was found by putting an image containing spots in known coordinates on the SLM. The resulting spots distribution was recorded using the CMOS sensor, and the coordinates for each spot in the sensor space were found. Afterwards, two coordinate transformation polynomials to calculate the $X_{SLM}$ and $Y_{SLM}$ coordinates in function of the $X_{CMOS}$ and $Y_{CMOS}$ coordinates were found using the least squares technique.

The phase distortion measurement on the interferogram was made using a four-step phase-shifting method. For this purpose, constant phase values of $\frac{\pi}{2}$, $\pi$, $\frac{3\pi}{2}$ and $2\pi$ were displayed on
Figure 2. Characterization curves for the working configuration at 442 nm. (a) Amplitude curve, (b) Phase curve.

the SLM and the four resulting interferograms were recorded. The phase characterization curve from the Figure 2(b) was used to obtain the equivalent gray level for each phase value. From the recorded interferograms, the phase $\phi(x_{\text{CMOS}}, y_{\text{CMOS}})$ on the CMOS plane was calculated, using the Le Carre algorithm [5]. The resulting phase map is shown in Figure 3(a). The discontinuities in this reconstructed phase can lead to mistakes when the coordinate transformation between CMOS and SLM planes is applied, so it was necessary to use a phase unwrapping algorithm (Figure 3(b)). The resulting phase $\phi_{\text{uw}}(x_{\text{CMOS}}, y_{\text{CMOS}})$ was evaluated in the SLM plane using the coordinate transformation functions calculated before, which result in $\phi_{\text{uw}}(x_{\text{SLM}}, y_{\text{SLM}})$ (Figure 3(c)). The compensation phase to be displayed in the SLM is the conjugate of $\phi_{\text{uw}}(x_{\text{SLM}}, y_{\text{SLM}})$. As the modulator used can only produce phase alterations between 0 and $2\pi$, the compensation phase to be used is given by:

$$\phi_{\text{CP}}(x_{\text{SLM}}, y_{\text{SLM}}) = 2\pi - (\phi_{\text{uw}}(x_{\text{SLM}}, y_{\text{SLM}}) \mod 2\pi)$$

where $\mod$ denotes the modulus operator.

The calculated phase $\phi_{\text{CP}}(x_{\text{SLM}}, y_{\text{SLM}})$ (Figure 3(d)) was finally displayed on the SLM in gray levels, using the SLM phase characterization curve shown in Figure 2.

4. Experimental Results

To check the compensation phase calculated before, it was displayed on the SLM and the resulting interferogram was recorded. In Figure 4(a), the compensation phase was applied only on a small square region on the SLM. In this selected region, it can be seen how the effect produced by the optical system aberrations is eliminated in contrast to the region outside the square. In Figure 4(b), the compensation phase was applied to the entire region of the SLM recorded by the CMOS.

5. Conclusions

A method to measure and compensate the optical aberration using a reflective Spatial Light Modulator was presented. This method compensates all phase aberrations or distortions present in the experimental setup when the compensatory phase is displayed on the SLM. The coordinate transformation calculated lets the method be applied even for those systems where the sampling on the observation plane and the SLM plane is not the same.
Figure 3. Phase compensation method: (a) Phase recorded on the CMOS. (b) Unwrapped phase on the CMOS plane. (c) Unwrapped phase calculated on the SLM plane. (d) Compensatory phase in gray values.

Figure 4. Interferograms showing the results of aberration compensation: (a) Comparative image where the compensation was applied only to a small portion of the SLM. (b) Application of the compensation phase on the entire region of the SLM recorded by the CMOS.

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