

Computational Fourier Optics Simulation using a virtual laboratory

L. Remón

Postdoctoral Researcher
Escuela Técnica Superior de Ingeniería del Diseño
Valencia, Spain
lauremar@upvnet.upv.es

V. Ferrando

PhD Student
Escuela Técnica Superior de Ingeniería del Diseño
Valencia, Spain
viferma1@upv.es

L. M. Sánchez Ruiz

Professor
Escuela Técnica Superior de Ingeniería del Diseño
Valencia, Spain
lmsr@mat.upv.es

E. Ballester

Professor
Escuela Técnica Superior de Ingeniería del Diseño
Valencia, Spain
eballest@isa.upv.es

W. D. Furlan

Professor
Departamento de Óptica
Valencia, Spain
walter.furlan@uv.es

J. A. Monsoriu

Professor
Escuela Técnica Superior de Ingeniería del Diseño
Valencia, Spain
jmonsori@fis.upv.es

Keywords: Zernike, aberrations, simulation, image optical quality

INTRODUCTION

The optical quality of any optical element is limited by wavefront aberrations and diffraction. The diffraction effects are associated with limited aperture size (more

noticeable with small pupil). However, with pupil larger than 3.00 mm the aberrations are the main contributor to image degradation [1].

Nowadays, the use of wavefront sensors and the Zernike expansion are used to describe the wavefront error of any optical element. The wavefront error provides information about the type and magnitude of each aberration presented in the optical element and it is an accepted measurement in research to know the optical quality.

From the measured wavefront error, the Point Spread Function (PSF) can be calculated using Fourier analysis. The PSF is commonly used to describe the performance of optical systems [2].

The appearance of any image can be computed only convolving the initial object by the PSF. The Fourier transform is a versatile tool used in many fields of science, mathematical or physical tool to alter a problem into one that can be more easily solved [3].

In this work we present a virtual laboratory developed in MATLAB GUI (Graphical User Interface) to be used in Photonic Devices course at “Escuela Técnica Superior de Ingeniería del Diseño” as a computing tool which allows doing different Fourier optical computations and creating image simulations that include diffraction and aberrations.

As an example, this virtual laboratory allows the engineering students to know objectively how an optical system, such as an ophthalmic lens, provides the appearance of a determined scene or optotype. Moreover, the software allows visualizing what kind of aberrations affect more to the image quality, the interactions among them and the effect of the pupil size on the final image.

1 BASIC THEORY

Defocused images and optical computations were simulated numerically using the standard Fourier techniques by means of the Optical Transfer Function (OTF) computed for an optical system following the procedure sketched in *Fig. 1*.

The Zernike coefficients were obtained from the phase map, which is provided by commercial machines as do the topographers and the aberrometers, as

$$W(x,y) = \sum_{j=1}^M a_j Z_j(x,y), \quad (1)$$

where M is the number of Zernike modes employed in the wavefront reconstructions, $Z_j(x,y)$ are the Zernike polynomials and $a_j(x,y)$ are the Zernike coefficients.

Then, the pupil function that incorporates the complete information about imaging properties of any optical system is calculated as

$$P(x,y) = A(x,y) \exp \left[-i \frac{2\pi}{\lambda} W(x,y) \right], \quad (2)$$

where $A(x,y)$ is a circular aperture representing the pupil with a normalized amplitude transmittance and λ is the computerized wavelength.

The Point Spread Function (PSF) and the OTF were both numerically calculated by means of a Fourier transform (FT). By multiplying the OTF with the Fourier spectrum of the set of optotypes or scene and doing an Inverse Fourier Transform (ITF), the simulated image of the test is obtained.

In the particular case of an ophthalmic lens the wavefront phase of Eq. (1) can be expressed as

$$W(x,y) = a_3 Z_3(x,y) + a_4 Z_4(x,y) + a_5 Z_5(x,y), \quad (3)$$

where $Z_3(x,y)$, $Z_4(x,y)$, and $Z_5(x,y)$ are the Zernike polynomials corresponding to astigmatism at $45^\circ/135^\circ$, defocus, and astigmatism at $0^\circ/180^\circ$, respectively.

The conventional script notation of an ophthalmic lens Sphere (S), Cylinder (C) and Axis (α) ($S; C \times \alpha$) was converted to power vector coordinates (M, J_0, J_{45}) using the following equations

$$M = S + \frac{C}{2}, \quad J_0 = -\frac{C}{2} \cos 2\alpha, \quad J_{45} = -\frac{C}{2} \sin 2\alpha \quad (4)$$

Then, the Zernike aberrations coefficients were calculated using the following expressions [4]

$$a_3 = \frac{-J_{45} R_p^2}{2\sqrt{6}}, \quad a_4 = \frac{-M R_p^2}{4\sqrt{3}}, \quad a_5 = \frac{-J_0 R_p^2}{2\sqrt{6}} \quad (5)$$

R_p being the pupil radius.

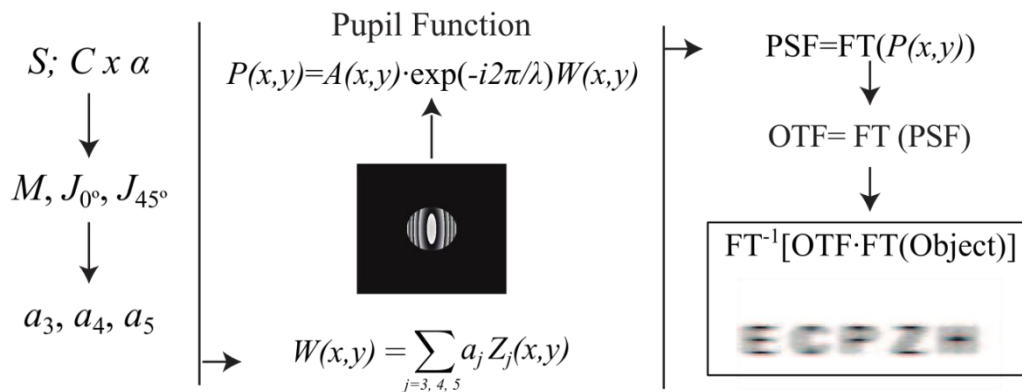


Fig. 1. Scheme of the optical computations using Fourier techniques

1.1 Graphical interface

The designed graphical interface using MATLAB GUI is shown in Fig. 2. Following the input and output parameters are described.

INPUT PARAMETERS

General Parameters

- Wavelength of the light in nm (λ).
- Viewing distance in m.

- Pupil radius in mm (R_p).

Object test

- Choose the object test [optotype (a set of characters, boxes or the Siemens star) or natural scene] used in the simulation. Representation of the object test.

Zernike coefficients

The Zernike coefficients are calculated up to $M = 14$. The software allows different ways of choosing the Zernike coefficients:

- 1) Introduce the values of all the Zernike coefficients in microns.
- 2) Calculate them from a conventional script notation ($S; C \times \alpha$) of an ophthalmic lens by using Eq. (4) and Eq. (5). Introduce the Sphere, Cylinder and Axis of a lens.
- 3) From an aberration map provided by commercial machines as do the topographers and the aberrometers. *Option: Load.*

OUTPUT PARAMETERS

Wavefront map obtained using Eq. (1). The representation of the wavefront map gives information about the aberrations presented in the optical system.

Point Spread Function (PSF) calculated by means of a Fourier transform (FT) of Eq. (2). The representation describes the response of an imaging system to a point source or point object.

Simulated Image appearance of a determined scene or optotype (without tilts and up to fourth order Zernike polynomials)

2 RESULTS

Using the designed MATLAB GUI, engineering students perform some educational studies of the image forming quality. Furthermore, the effect of the defocus on different pupils size may also be compared.

2.1 Effect of defocus and astigmatism on the simulated image

Ophthalmic lenses with different spherical and cylindrical powers ($S; C \times \alpha$) have been simulated in order to qualitatively study the effect of the second order aberrations in known conditions.

Fig, 1 shows the simulated images of a set of optotypes under a monochromatic illumination ($\lambda = 635 \text{ nm}$) and with $R_p = 2.25 \text{ mm}$.

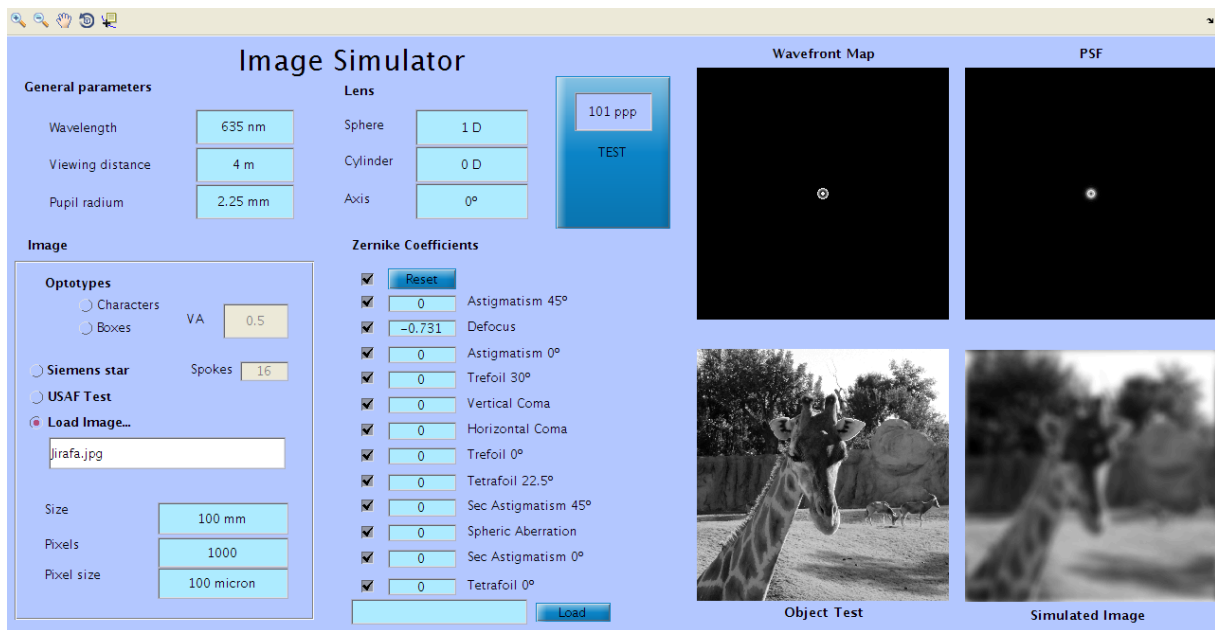


Fig. 2. Graphical interface of the MATLAB GUI.

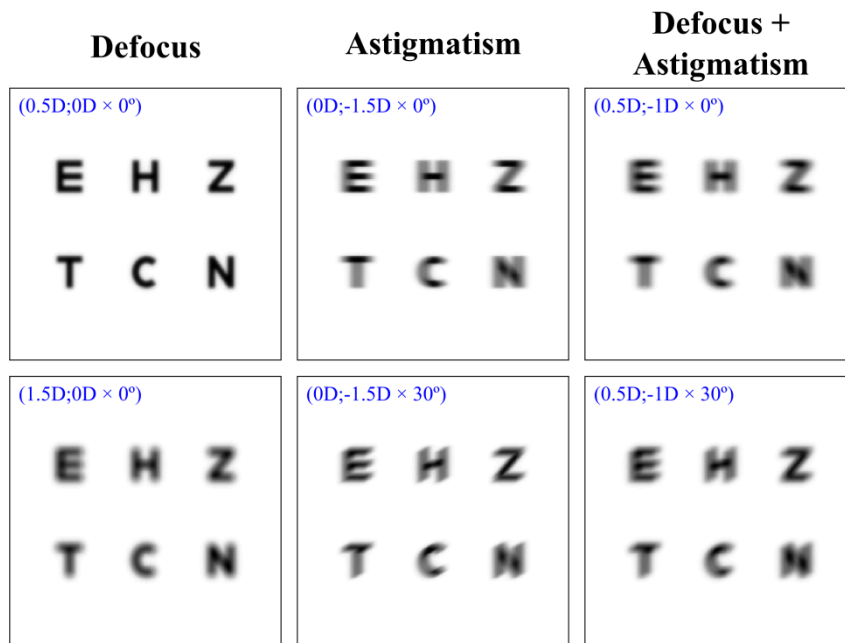


Fig. 3. Image forming simulation for ophthalmic lenses with different spherical and cylindrical powers, $R_p=2.25$ mm

2.2 Interaction between spherical aberration and defocus to improve the visual performance

Engineering students notice how pairs of Zernike modes interact to increase and decrease the visual performance.

Fig. 4 shows the interaction between two aberrations, spherical aberration $a_{12}= 1\mu\text{m}$ and different values of defocus a_4 . The combination of both aberrations provides better image than having only spherical aberration.

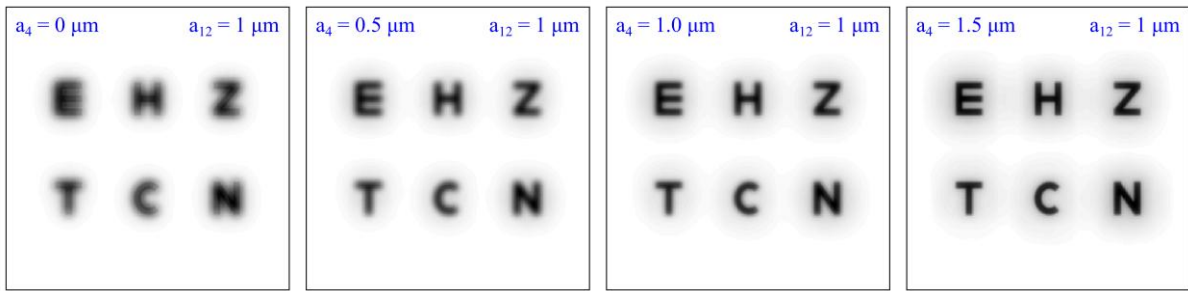


Fig. 4. Image forming simulation. Interaction between two Zernike modes (spherical aberration+ defocus)

2.3 Effect of pupil size in the simulated image

Finally, engineering students observe the effect of the pupil size on image forming.

Fig. 5 shows the simulations for two different size pupils ($R_p=2$ mm and $R_p=5$ mm) and two different defocus ($S=0$ D and $S=0.25$ D). For small pupil sizes, diffraction effects are predominant over the aberrations.

However, the blurring effect of aberrations becomes more noticeable for large pupils.

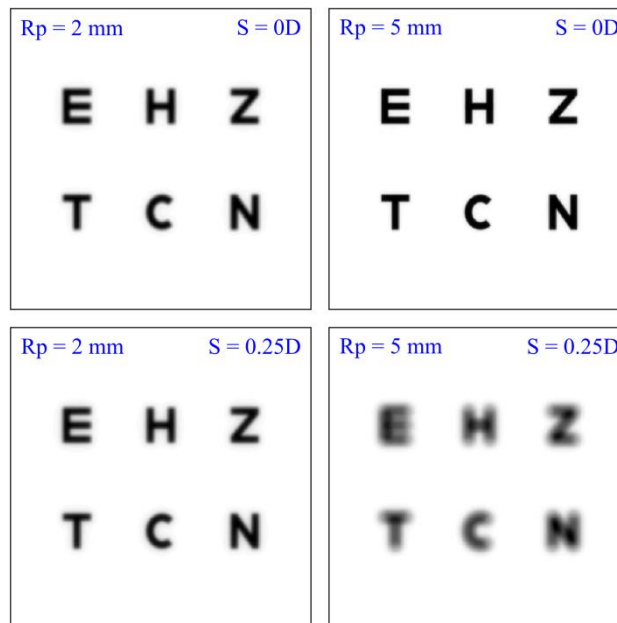


Fig. 5. Simulated image for different pupils size

3 SUMMARY AND ACKNOWLEDGMENTS

We have presented a virtual laboratory developed in MATLAB GUI that is useful to explain the effect produced by different aberrations when forming images by simulating the image forming capabilities of the configured pupil.

With this software engineering students can simulate the image of a known object provided by any combination of Zernike function by means of a friendly interface.

This research was supported by *Ministerio de Economía y Competitividad* (FIS2011-23175) and *Generalitat Valenciana* (PROMETEOII/2014/072 and ACOMP/2014/180).

REFERENCES

- [1] Hopkins, H.H. (1985) Image formation by a general optical system. 1: General Theory, *Applied Optics*, Vol. 24, No. 16, pp. 2491-2505.
- [2] Born, M. and Wolf, B., (1993). *Principles of Optics*. Ed. 6 Oxford: Pergamon Press.
- [3] Goodman, J.W. (1996). *Introduction to Fourier Optics*. Ed. 2 New York: Mc Graw-Hill.
- [4] Thibos L.N., Hong X., Bradley A. and Applegate R.A. (2004), Accuracy and precision of objective refraction from wavefront aberrations, *Journal of Vision* Vol. 4, No. 4, pp. 329-351.