

Birongchigram processing method for quantitative evaluation of optical focusing mirrors

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ABSTRACT

Since its proposal the Ronchi “ruling” test has been considered as the most remarkable technique of the Schlieren family. Despite being based on fringe pattern generation and commonly interpreted in a qualitative way, it was capable of achieving outstanding results in the detection of aberrations in optical surfaces. Given its theoretical straightforwardness, experimental simplicity and economic affordability in comparison to other methodologies in the field, in the present work is addressed the lingering issue of how to extract quantitative information from digital captures of this test. Such task was accomplished taking advantage of the improved Ronchi test with a square grid, from which it was possible to develop a mathematical model with foundation in the Fourier theory to describe its observations. Thereupon, it was devised a novel iterative algorithm grounded in Fourier phase measuring able to compute fairly accurate wavefront gradient estimations from a single “birongchigram” sample with grid defocus. This procedure is complemented by a mandatory integration algorithm that is based on the regularization theory. The overall proposed methodology was put to test in a large aspherical mirror, estimating a surface aberration profile with a P–V (peak to valley) ratio of 155 nm, value well in accord with the one reported by the commercial interferometric system used for validation.

1. Introduction

The Ronchi test was proposed in 1923 by the Italian physicist Vasco Ronchi. Since then, this procedure has been considered as one of the most powerful tools at the disposal of amateurish telescope makers. This methodology allowed a comparatively faster, simpler and/or cheaper optical testing of large focusing mirrors, critical during its figuring process [1].

A basic Ronchi test apparatus can be roughly described as the combination of a semi-punctual light source and an optical target consisting of a series of clear and opaque straight stripes alternating at a fixed spatial frequency [2], nowadays simply known as a “Ronchi ruling”.

As a result of being a direct derivation of the Foucault “knife-edge” test, the merit of the Ronchi test thus lies solely in the substitution of the knife-edge for a Ronchi ruling to be used as the system light transfer function. This simple interchange grants both richer and more detailed visual information all over the specimen surface, making the evaluation considerably less subjective.

In the past many works were dedicated to better understand, generalize and improve several aspects of this technique. Among the most remarkable variations can be named the null Ronchi test, designed to

increase the sensitivity of the procedure and its correlation with the Hartmann test [3,4]. Later on, the single side-band Ronchi test was proposed to substantially reduce the Talbot diffraction, diminishing effect commonly present in lateral shear interferometry at the time [5]. This was followed by the fringe scanning (phase measuring) Ronchi test, devised to handle the testing of fast aspherical (large aberration) surfaces with the aid of synchronous phase detection [6,7]. Finally, the extended source Ronchi test appeared to enhance the contrast and fringe visibility of the ronchigrams by taking advantage of the self-imaging phenomenon and the superimposition of multiple mutually incoherent Fresnel diffraction patterns [8].

Despite all this efforts, the methodology would never entirely escape the veil of subjectivity in which all optical testing techniques based upon generation of shadow patterns are commonly shrouded. As the years passed, all the Schlieren tests were almost completely abandoned in favor of other procedures considered as vastly superior at least in terms of precision, as is the case of interferometry [1,9].

More recently, the whole influence of the Ronchi test has been confined to the employment of its fixed periodicity grating as a complementary device in the implementation of several other optical procedures. For example, it was proposed an alternative model for the interpreta-

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tion of ordinary ronchigrams as interferograms in order to being able to calculate its irradiance profile [10]. Likewise brand-new kinds of interferometric systems were designed, such as the lateral shearing interferometer featuring two Ronchi phase gratings in series [11] and the common-path interferometer, a $4f$ arrangement with a Ronchi ruling as spatial filter [12].

On the other hand, the study of the Ronchi test in its original form is currently almost exclusively supported by several computational models and algorithms for the simulation and comparative analysis of its fringe maps. Some interesting instances are a simulation model based on the exact ray tracing theory [13], an algorithm for estimating the aberration coefficients from which a synthetic wavefront and its associated ronchigram were generated [14], and a computational model for correlating experimental and simulated bironchigrams through genetic algorithms to evaluate surface parameters and errors [15]. As can be inferred, all of them are meant to carry out direct comparisons between real and artificial samples with the aid of a computer, and not intended for the indirect measurement of the actual aberration profile of the optical device being tested.

For this reason, in this paper we take advantage of the square-grid Ronchi test [16] in order to increase the practical utility of the original method. Through this particular testing setup it was possible to establish a clear correlation between a crossed gratings pattern model for the calibration of a fringe projection profilometer [17] and the irradiance distribution of a bironchigram sample. The characteristics of such model are consistent with the physical theory, hence allowing the usage of the Fourier phase measurement method for our purposes as well.

In combination with the sinusoidal ronchigram model of the fringe scanning Ronchi test [6], it allowed us to devise an innovative iterative algorithm for wavefront gradient estimation from a single bironchigram sample with grid defocus produced by an optical focusing mirror. This methodology turns out to be considerably superior to the Foucault quantitative evaluation method [18] since it only requires a single capture to perform a full gradient estimation instead of several consecutive dozens, while also avoids the necessity of performing a 90° rotation of the specimen, operation that represents a potential source of human and/or mechanical errors.

In the meantime, the procedure employed to carry out the mandatory integration process of these estimated gradient fields is the improved resolution of a regularized quadratic cost function [19] by means of an optimized linear conjugate gradient method [20]. This particular integration process allows an easier establishment of the region of interest (ROI) confined by the system exit pupil, and whose omission can cause a serious error propagation in the analysis [21].

The proposed methodology was tested in a large aspherical mirror achieving a level of precision akin to that of the commercial interferometric system employed for validation, outcome that constitutes the main objective and fundamental contribution of this work. Thus, while this renewed optical method is ideal and specifically aimed for small amateurish workshops, it also exhibits a sufficiently decent level of precision to be employed in modern laboratories and industrial manufacturing as a complementary quality test.

2. Theoretical background

The basic setup for the Ronchi test positions the concave specimen of superficial diameter D to be analyzed with its optical axis z facing forward. At the distance of its nominal curvature radius r a semi-punctual light source s is placed immediately adjacent to the z -axis avoiding the occlusion of the image. To produce the characteristic shadow fringes a Ronchi ruling of fixed spatial period p and perpendicular to the z -axis is located amid the focusing path at a distance l' referred from the center of curvature (see Fig. 1). Beyond this modulating screen an imaging system situated at the image plane would detect the otherwise merely expanded straight stripes bending very slightly over the mirror surface due to the grating defocusing, the imperfections and intrinsic morphol-

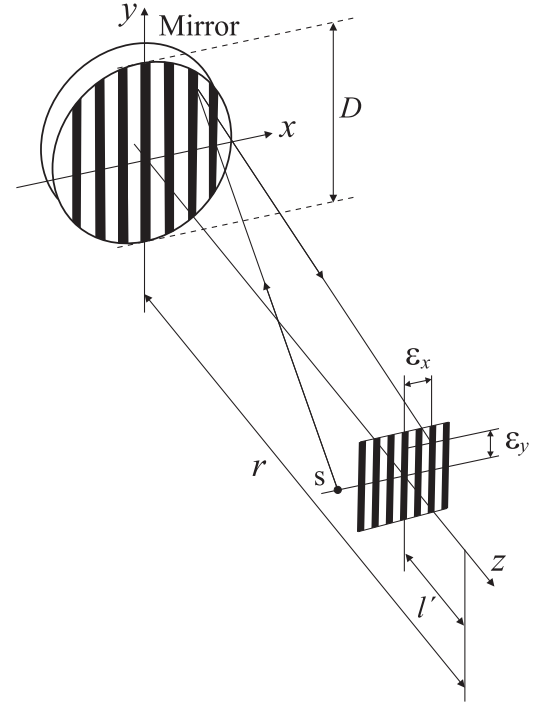


Fig. 1. Basic geometry of the Ronchi test arrangement (distances and proportions exaggerated for visualization purposes).

ogy of the piece. This effect can be considered as an indication of the presence of the transverse aberrations ϵ_x and ϵ_y [2].

2.1. Physical theory

From the standpoint of physical optics such observable fringe combination can be interpreted as a product of the interference and diffraction effects. Therefore, considering this fringe map as an interferogram for which the Ronchi ruling has produced many diffracted orders, the wavefront at the exit pupil plane when the system is evenly illuminated can be represented as follows: [2]

$$F(x, y) = \begin{cases} \exp[i2\pi W(x, y)/\lambda] & \text{inside the circular aperture,} \\ 0 & \text{otherwise,} \end{cases} \quad (1)$$

where $i = \sqrt{-1}$, $W(x, y)$ stands for the wavefront deformation function and λ for the wavelength. Hence, if the Ronchi ruling is treated as a spatial filtering mask in the transform plane $M(u, v)$ the complex amplitude function in the observation plane would be given by [2]

$$G(x_o, y_o) = \iint_{-\infty}^{\infty} F(x, y) dx dy \iint_{-\infty}^{\infty} M(u, v) e^{i(2\pi/\lambda r)[(x_o-x)u + (y_o-y)v]} du dv, \quad (2)$$

which represents an acceptable physical model for virtually any kind of modulation screen. However, solving this integral formulation could become cumbersome when a Moiré-like pattern is formed [22], which occurs when two or more rotated ruled patterns overlaid, precisely the case of a bironchigram sample.

On the other hand, it has been proven that the geometrical theory arrives at the same result when the grating frequency is relatively low [2]. Fortunately, the aforementioned is one of the essential conditions in ronchigram generation since fringe oversaturation is always avoided.

2.2. Geometrical theory

From the point of view of geometric optics the stripes of a ronchigram can be regarded simply as shadows backprojected directly from

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