Evaluation of the increment of the sampling in optical testing using substructured Ronchi gratings

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\textbf{Abstract.} In this paper, we use Ronchi substructured gratings to evaluate the increment of the accuracy in optical testing using a liquid crystal display. For this, we perform a comparison between the aberration function and the wavefront obtained with classical Ronchi gratings against the ones obtained using substructured Ronchi gratings. This analysis is performed for different gratings positions, both outside and inside of focus. We show the results obtained in the laboratory for a concave spherical mirror of 57.27 mm diameter and a radius of curvature of 397.55 mm. We conclude that by using substructured Ronchi gratings we can test a larger area of ronchigram.

\section{1. Introduction}
The Ronchi test is one of the simplest and most powerful methods to evaluate and measure the aberrations of an optical system, because the surface errors can be estimated through the deviation of the pattern from the calculated pattern [1]. This method consists of observing the reflection of a ray of light coming from an array of transparent and opaque parallel and equally spaced lines, positioned near the center of curvature of the test surface, producing an interference pattern that can be observed in the exit pupil.

With the aim of increasing the sharpness of the observed fringes on the interference patterns in the Ronchi test a configuration of unequal widths of the opaque and transparent lines of the grating are used. If the widths of the transparent lines are larger than the opaque lines the gratings is called positive, and the grating is called negative when the opaque lines are larger than the transparent lines [2].

Here used a combination of several Ronchi ruling to create the substructure of the variable frequency ruling, one example of this type of substructured gratings are the gratings called Katyl [3].

In this paper we propose to use substructured grating with different sequences in order to increase the sharpness of the fringes and likewise increase the sampling over the surface under test compared with the classical Ronchi gratings. For this, in Section 2 we show the functions for the structured grinds, in Section 3 we describe the experimental setup. Next, in Section 4 we show the experimental results an finally we show our conclusions.
2. Substructured gratings

Each substructured grating with period $d$, is composed of a sequence of $m$ consecutive lines of equal width $h$, and a transmittance $t_n$. Each strip is transparent or opaque depending of the coding sequence used [4]. The transmittance coefficients $B_n$ of these substructured Ronchi gratings can be calculated using the Fourier Theory as follows.

M. Campos and F. Granados [4] calculated the role of substructured grids of binary sequences for lengths $m = 7$ and 8-bits, these gratings are shown in Figure 1.

The ruling function for negative and positive 7-bits grating is given by

$$
M^7+(x_r) = \frac{4h}{d} + \frac{i}{2\pi} \sum_{n=1}^{\infty} B_n^7+ \exp\left(\frac{i2\pi nx_r}{d}\right),
$$

$$
M^7-(x_r) = \frac{3h}{d} + \frac{i}{2\pi} \sum_{n=1}^{\infty} B_n^7- \exp\left(\frac{i2\pi nx_r}{d}\right),
$$

Were the coefficients $B_n^7+ y B_n^7-$ are

$$
B_n^7+ = \exp\left(-\frac{i6\pi mh}{d}\right) - 1 + \exp\left(-\frac{i12\pi mh}{d}\right) - \exp\left(-\frac{i10\pi mh}{d}\right)
$$

$$
B_n^7- = \exp\left(-\frac{i10\pi mh}{d}\right) - \exp\left(-\frac{i6\pi mh}{d}\right) + \exp\left(-\frac{i14\pi mh}{d}\right) - \exp\left(-\frac{i12\pi mh}{d}\right)
$$

Both positive and negative 7-bits grating $h = d/7$.

For the substructured grating with binary sequence of 8-bits positive and negative (Table 1), the function is given by

$$
M^8+(x_r) = \frac{5h}{d} + \frac{i}{2\pi} \sum_{n=1}^{\infty} B_n^8+ \exp\left(\frac{i2\pi nx_r}{d}\right),
$$

$$
M^8-(x_r) = \frac{3h}{d} + \frac{i}{2\pi} \sum_{n=1}^{\infty} B_n^8- \exp\left(\frac{i2\pi nx_r}{d}\right)
$$

And the coefficients $B_n^8+ y B_n^8-$ are of the form

$$
B_n^8+ = \exp\left(-\frac{i10\pi mh}{d}\right) - \exp\left(-\frac{i14\pi mh}{d}\right) - \exp\left(-\frac{i10\pi mh}{d}\right)
$$

$$
B_n^8- = \exp\left(-\frac{i10\pi mh}{d}\right) - \exp\left(-\frac{i6\pi mh}{d}\right) + \exp\left(-\frac{i16\pi mh}{d}\right) - \exp\left(-\frac{i14\pi mh}{d}\right)
$$

And in this case $h = d/8$. 

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The binary sequence for the positive and negative substructured gratings 7 and 8-bits showing in the Table 1 and are given by

**Table 1.** Binary sequence for the substructured gratings 7 and 8-bits.

| Grating type Katyl | Positive  | Negative |
|--------------------|-----------|----------|
| 7-bits             | 1110010   | 0001101  |
| 8-bits             | 11100110  | 00011001 |

3. **Setup**

Instead of using a conventional Ronchi grid, we use a liquid crystal display (LCD) which displays the classical and substructured binary Ronchi grids. The LCD is a spatial light modulator (XGA2) with a spatial resolution of 1024x768 pixels; the dimensions of the active pixels are 23x16 µm. The LCD was mounting on one linear stage xy, this mount on the lab jack for a more precision alignment (Figure 2).
Figure 2. Experimental setup to the Ronchi test a) lateral view, b) diagram of the test and c) posterior view.

The illumination source is a light-emitting diode (LED) of dominate wavelength 700 nm and a diameter of 5 mm. The images were captured with a Nikon camera model coolpix 8700, with a CCD sensor of 8.0 megapixels, and an optic zoom of 8x (Figure 3).

4. Experimental results
For the experiments we use a concave spherical mirror, which has a designed radius of curvature of 397.55 mm and 57.27 mm of diameter. The ronchigrams obtained with classical and substructured Ronchi gratings with a defocus of 3.15 and 3.79 cm inside of focus by 7 and 8-bits gratings respectively, are showing in the Table 2.

The classical and the substructured Ronchi gratings used for the analysis of the surface under test have a bit length to $h = 2$ pixels = 46 $\mu$m, and with their slits oriented vertically.
Table 2. Classical vs substructured grating.

| Type                      | Ronchigram | Aberration function | Wavefront |
|---------------------------|------------|---------------------|-----------|
| **Positive 7-bits**       | ![Ronchigram](positive_7_bits_classical_grating.png) | ![Aberration function_7_bits_classical_grating.png] | ![Wavefront_7_bits_classical_grating.png] |
| **Classical grating**     | ![Ronchigram](positive_7_bits_substructured_grating.png) | ![Aberration function_7_bits_substructured_grating.png] | ![Wavefront_7_bits_substructured_grating.png] |
| **Negative 8-bits**       | ![Ronchigram](negative_8_bits_classical_grating.png) | ![Aberration function_8_bits_classical_grating.png] | ![Wavefront_8_bits_classical_grating.png] |
| **Substructured grating** | ![Ronchigram](negative_8_bits_substructured_grating.png) | ![Aberration function_8_bits_substructured_grating.png] | ![Wavefront_8_bits_substructured_grating.png] |

In the Table 2 for the fringes sampling in the Ronchigrams, with classical gratings it can be seen that the sampling is smaller than the one derived with the substructured gratings. This fact is seen looking the number of dark fringes in the Ronchigrams; besides, the fineness of the fringe is improved with the proposed substructured gratings. With respect to the wavefront graphs, as result from the improved information from the Ronchigrams, more lines are scanned from the fringes for the substructured rulings.

5. Conclusions
We have studied, for the Ronchi test, the use of classical and substructured gratings, for improving the quantitative information for the wavefront under analysis. As result the sampling area of the Ronchigrams, used substructured rulings, is increased because more fringes with better fineness are observed. The grating used was 7 and 8-bits, positive and negative.
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