Ronchi test with variable-frequency rulings

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Abstract. We present a new method for testing an optical surface. It uses the Ronchi test with variable-frequency rulings and a liquid-crystal display. The rulings can be formed by substructuring the spacing of a Ronchi ruling or combining several classical Ronchi rulings in a single variable-frequency ruling. This change allows us to observe smaller defects on the surface, because it enlarges the spatial-frequency domain of the ruling, and a larger dynamic range of detection of the Ronchi test can be obtained instead of increasing the resolution of the detection of the Ronchi test by iteratively changing classical Ronchi rulings with higher line density. As a result, we have found that it is possible to measure defects on a optical surface that are of size $\geqslant 57$ nm ($\lambda/11$). [DOI: 10.1117/1.3072956]

Subject terms: Ronchi test; optical testing; fringe projection.

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1 Introduction

For many years, the Ronchi test has been considered a very powerful optical test for concave optical surfaces and complete optical systems. Some of its advantages are that it is quick to understand and simple to assemble in the laboratory or optical workshop. According to Cornejo-Rodríguez, the pattern produced by the Ronchi test has two equivalent interpretations.[1] One is geometrical, whereby the Ronchi fringes can be studied as shadows of the ruling bands, and the other is from a physical point of view, whereby the fringes are generated by diffraction and interference. Moreover, when a ruling is placed near the center of curvature of a mirror, the image of the grating is superimposed on the grating itself, generating a kind of moiré pattern, and it can be applied to test the quality of an optical surface. If the angle between the two gratings is increased, then the spacing decreases. On the other hand, Creath and Wyant have mentioned that if the gratings are not identical straight lines, then the moiré pattern does not have equal-spaced fringes.[2]

In this work, we superimpose Ronchi rulings with different frequencies on an LCD without a tilt angle between them. Therefore the resulting ruling has variable frequency, since the spacing has thinner lines than the classical Ronchi rulings; thus we can enlarge the spatial frequency of the ruling in order to test an optical surface within a single ruling.

This paper is organized as follows: In Sec. 2, background is given. In Sec. 3 the LCD calibration method is explained. In Sec. 4 the experimental setup is presented. The main experimental results are discussed in Sec. 5. Our conclusions are presented in Sec. 6.

2 Background

According to Mora-González and Alcalá-Ochoa, the typical Ronchi ruling has been replaced by an LCD as a low-cost display to test polished mirrors.[3] Also, Alcalá-Ochoa et al. have used the classical Ronchi test to measure flat surfaces by modifying the classical Ronchi setup, so that the Ronchi rulings are computed and displayed by the LCD.[4] Furthermore, Castro-Ramos et al. have done phase shifting by means of an LCD.[5]

We have found advantages in the use of an LCD in that it is possible to change the structure of the ruling easily without physical contact. It is important to mention that not only several classical rulings with unequal widths of lines, such as positive or negative rulings (Murty and Cornejo,[6] Cornejo-Rodríguez et al.[7]) can be displayed by means of an LCD, but also Katyl-type rulings (Katyl,[8] Cornejo-Rodríguez et al.[9]).

On the other hand, the LCD introduces some complex diffraction effects, as when a convergent optical system has

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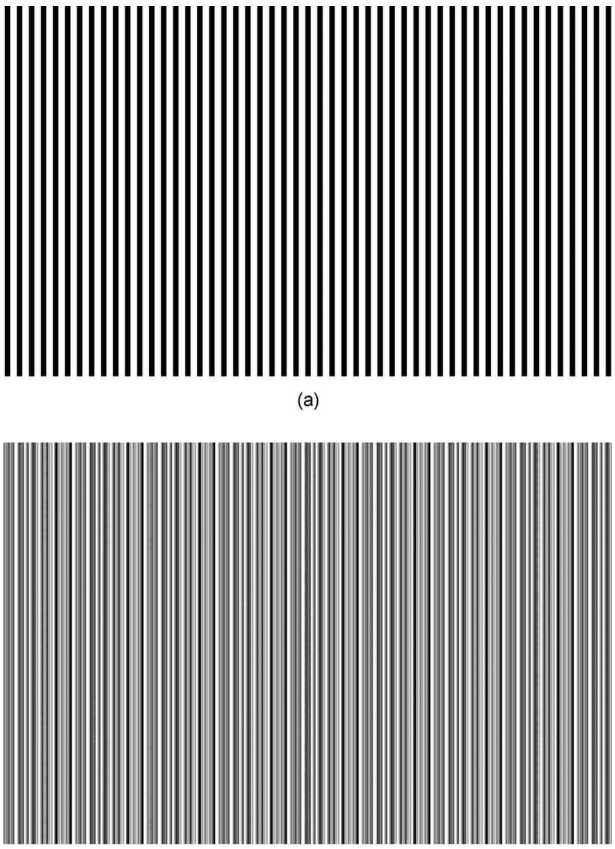
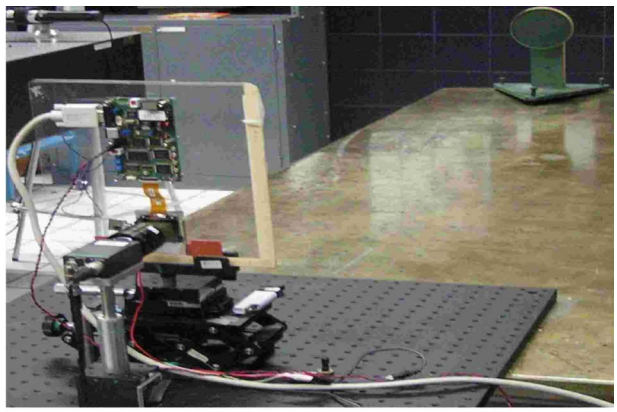


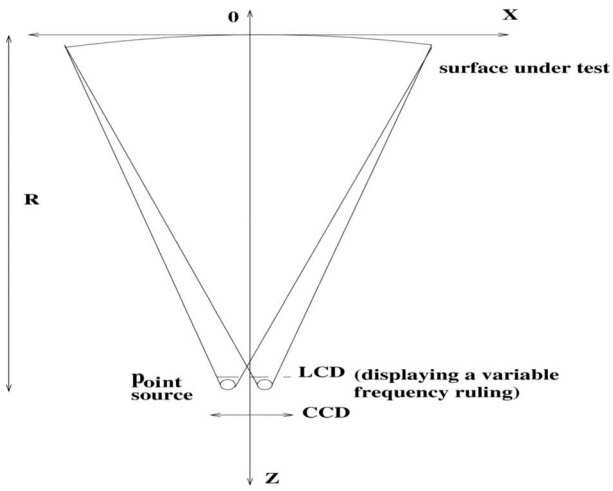
(a)

(b)

Fig. 1 (a) Classical Ronchi ruling of 50 lines per inch, and (b) variable-frequency ruling with three different frequencies of 50, 86, and 133 lines per inch.



(a)



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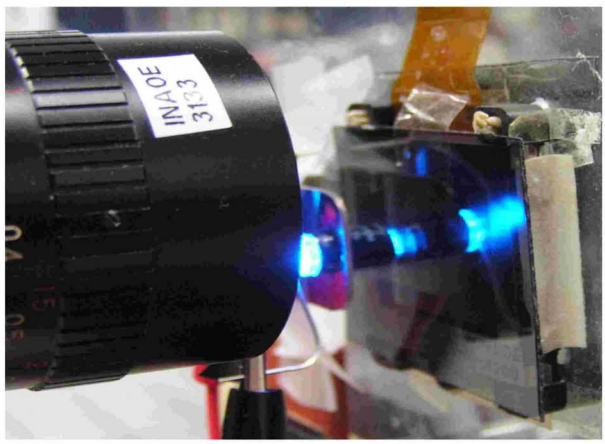


(c)

Fig. 2 (a) Experimental setup for the Ronchi test using an LCD, (b) setup diagram, and (c) a point illumination source for this test, mounted on a plastic plate.

been tested with a Ronchi test and the LCD is used as an amplitude sinusoidal grating (Mora-González and Acalá-Ochoa[10]). In other work, a qualitative study of the relation between LCD pixel shape and far-field diffraction patterns has been obtained by Fernandez et al.,[11] and also a novel proposal for optical testing using a single-slit system with a spatial light modulator (SLM) to avoid several diffraction effects is presented by Liang and Sasian.[12]

An interesting consequence of using a variable-frequency ruling in optical testing can be observed by comparing it with the null Ronchi-Hartmann test used by Luna et al.[13] In that paper, the authors proposed a criterion to estimate the optimal width of a Ronchi fringe by using optical and statistical conditions of the deformations on the surface under test and the detector size. With this method, it is possible to investigate different magnitudes of peak-valley errors on the figure of the surface. When a variable-frequency ruling is used, it is possible to observe simultaneously different defects, so that to search for errors on the order of $\lambda/2$, a Ronchi ruling of 50 lines per inch is suitable. If now we are looking for errors on the order of $\lambda/6$, a Ronchi ruling of 86 lines per inch can be used, and for errors of $\lambda/10$, a Ronchi ruling of 133 lines per inch. Therefore, if a variable-frequency ruling with three different frequencies is simultaneously contained in a single ruling instead of using a classical Ronchi ruling, it is possible simultaneously to observe errors on the surface over a larger dynamic range of detection from $\lambda/2$ to $\lambda/10$.[13]

In this work we analyze the use of multiple frequencies within a Ronchi ruling by using an LCD. In the classical use of this technique, a ruling with only one frequency for its lines yields information about irregularities on the sur-

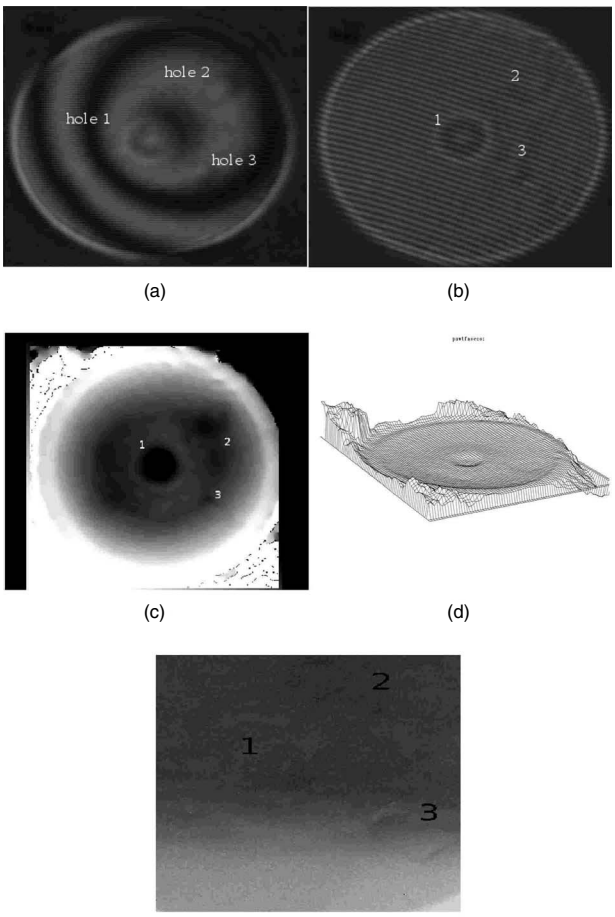


Fig. 3 (a) Zaygo interferogram for the quasiparabola under test; (b) Zaygo interferogram for the same surface with tip-tilts to measure the deformations on the holes; (c) unwrapped phase, with the gray scale (heights) in nanometers; (d) surface shape; and (e) Foucaultgram. The axis scales are in millimeters.

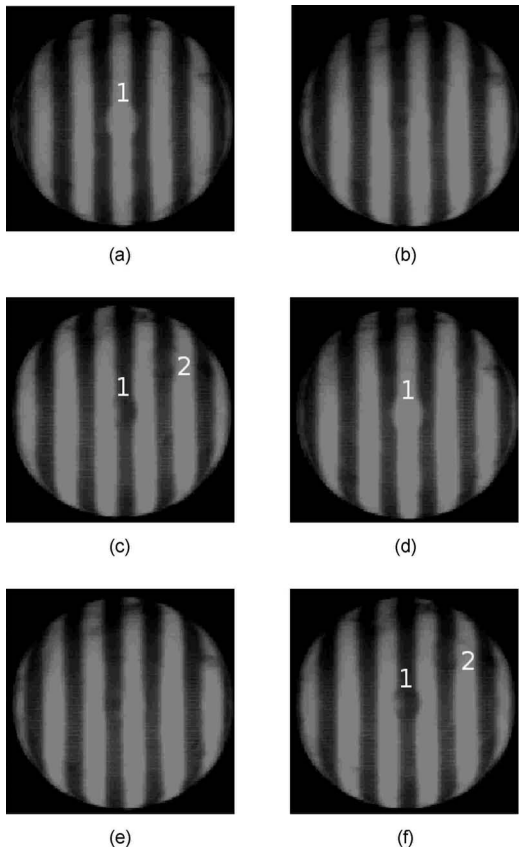


Fig. 4 Ronchigrams obtained with a classical Ronchi ruling of 50 lines per inch to scan the deformations on the mirror.

face being tested, but the size scales, being related to the spatial frequency, lie within a limited range. Thus, to enlarge the range of spatial frequencies, several rulings must be employed separately. We generated our variable-frequency ruling using an LCD, which allows an easy change of the ruling spacing. Here, we combine several frequencies within a single ruling; consequently one can observe a wider range of spatial frequencies (from $\lambda/2$ until $\lambda/11$).

3 LCD Calibration Method

The proposed LCD calibration method displays a Ronchi ruling image of 1024×768 pixels on an LCD. Our method is based on two scaling factors. The first one relates the physical dimensions of the LCD (25.4 mm=1 in.) and the size of the image produced by the ruling (1024 pixels). Thus, the first scaling factor is obtained as follows:

$$1\ \text{pixel} = (1\ \text{pixel})\frac{25.4\ \text{mm}}{1024\ \text{pixels}} = 0.024\ \text{mm} \approx 0.0009\ \text{in.} \tag{1}$$

The second factor is related to the line width (ΔL) in a Ronchi ruling of 50 clear lines and 50 opaque lines per inch,

$$\Delta L = (1\ \text{line})\frac{25.4\ \text{mm}}{p} = 0.254\ \text{mm}, \tag{2}$$

where $p=100$ lines. The line width in pixels (ΔL_{pix}) viewed from the Ronchi ruling image can be obtained when the size of a pixel and a line are both expressed in millimeters; thus the following relation is obtained:

$$\Delta L_{\text{pix}} = \frac{0.254\ \text{mm}}{0.024\ \text{mm}} \approx 10\ \text{pixels}. \tag{3}$$

Accordingly, a computer program displayed on the LCD 50 clear lines and 50 opaque lines, with a spacing of approximately 10 pixels between them; thus a Ronchi ruling image of 1024×768 pixels is input to the LCD. See Fig. 1(a).

Three types of Ronchi rulings of 50, 86, and 133 lines per inch were generated digitally, following the two scaling factors described. Then, the three images were added to obtain a variable-frequency ruling image on the LCD, such

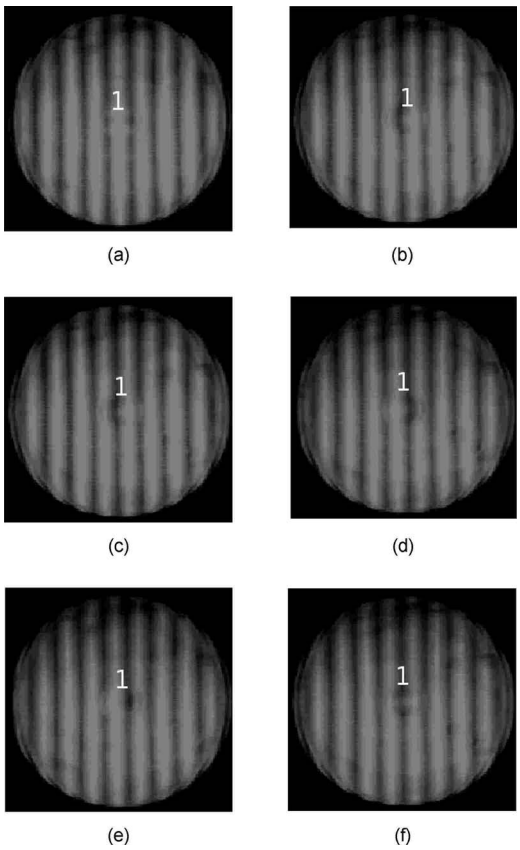


Fig. 5 Ronchigrams obtained with a classical Ronchi ruling of 86 lines per inch to scan the deformations on the mirror.

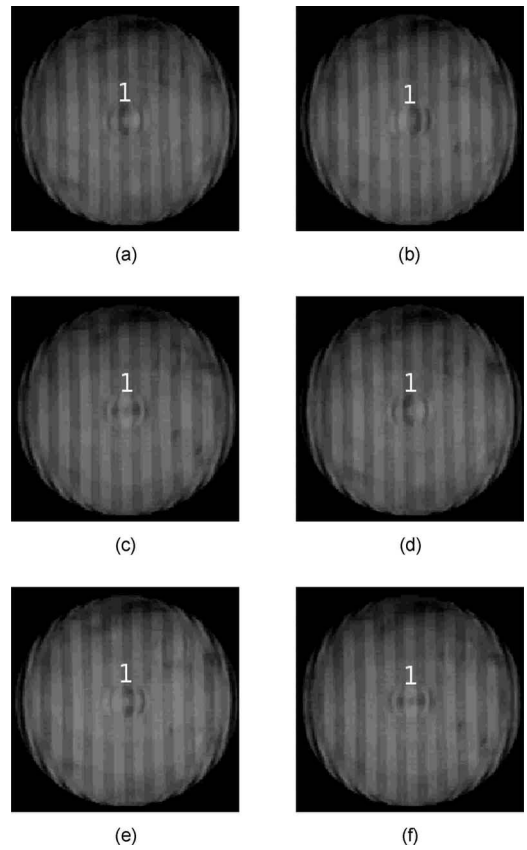


Fig. 6 Ronchigrams obtained with a classical Ronchi ruling of 100 lines pr inch to scan the deformations on the mirror.

as that shown in Fig. 1(b). Finally, we notice that the quality of the Ronchi ruling image can be improved obtaining the negative of the image by means of digital image-processing software.

4 Experimental Setup

In Fig. 2(a), the LCD is shown on a mount, which allowed sufficient lateral displacement of the ruling to scan the whole surface. Furthermore, to obtain homogeneous light an axial displacement is introduced, producing classical defocusing in order to generate different numbers of fringes. The axial displacement was obtained with nanometric screws.

The performance of Ronchi tests using the LCD and the classical ruling is the same. In Fig. 2(b), the wavefront produced by the point source sends the ruling information to the mirror under test, and when the light returns, it impinges on the LCD, where the image of the ruling is being displayed. Thus, the Ronchigram is acquired by a CCD placed in the observation plane in the Ronchi test.

The LCD used for this experiment with the Ronchi test is a spatial light modulator (XGA2 SLM), which displayed binary patterns with a spatial resolution of 1024 $\times$768 pixels. In order to observe an image on the LCD, two additional polarizers rotated 90 deg for maximum contrast are required. The first polarizer is placed on the side that goes to the mirror under test, and the second polarizer on the side of the observation plane of the Ronchi test; see Fig. 2(c). The illumination source consists of a spatially incoherent (LED), and it is placed as near as possible to the second polarizer.

5 Experimental Results

The surface under test was a quasiparabolic mirror (QPM) (rc=2400 mm and d=150 mm) in a final polishing process, and subjected to three particular deformations. The deformations were produced with a polishing tool statically working with a polisher of 1-μm grit for periods of 1 min, 30 s, and 20 s for hole 1, hole 2, and hole, 3 respectively. See Fig. 3(a) and 3(b).

The Zaygo interferometer (essentially a noncontact Fizeau interferometer with a spherical reference lens) was

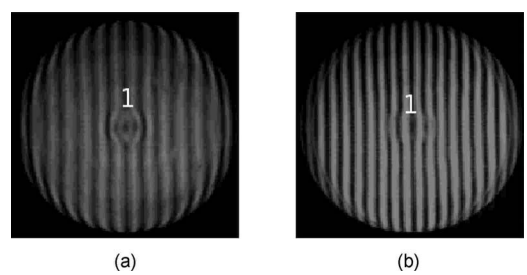


Fig. 7 Ronchigrams obtained with a classical Ronchi ruling of (a) 133 and (b) 170 lines per inch, maintaining the initial defocusing of Fig. 6.

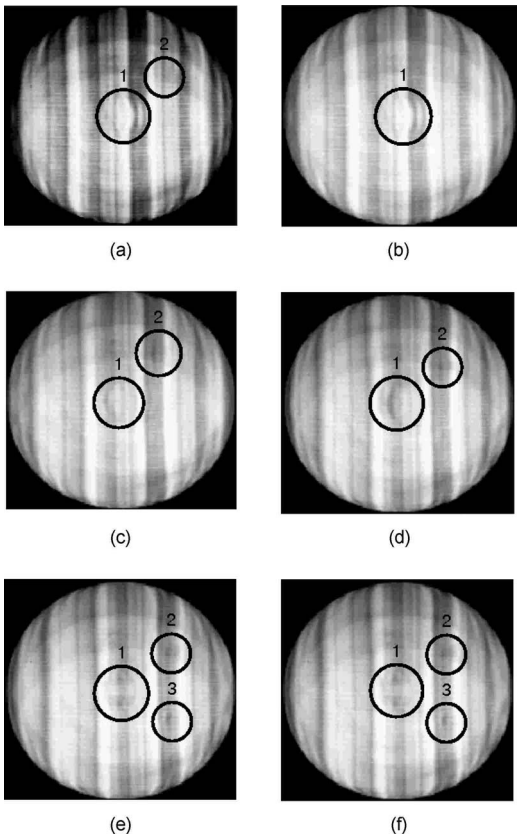


Fig. 8 Ronchigrams obtained with a variable-frequency ruling formed by three classical Ronchi rulings of frequency 50, 86, and 133 lines per inch.

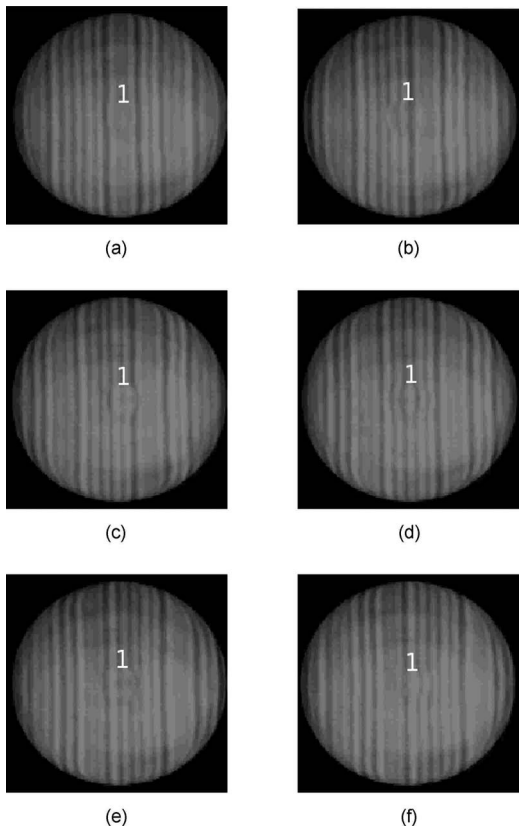
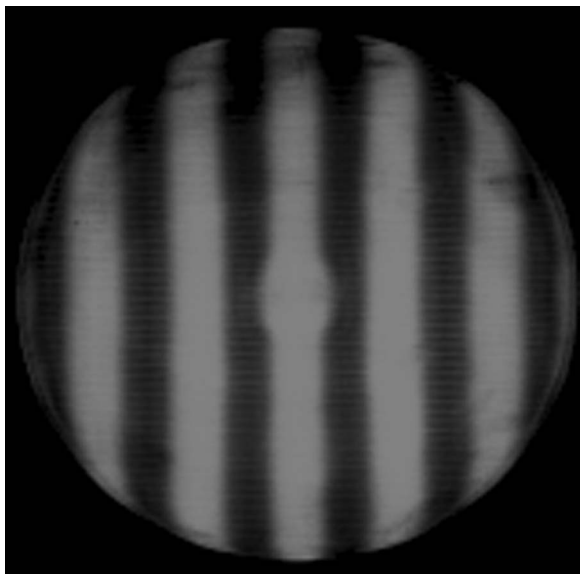


Fig. 9 Ronchigrams obtained with a variable-frequency ruling formed by three classical Ronchi rulings of frequency 100, 133, and 170 lines per inch.

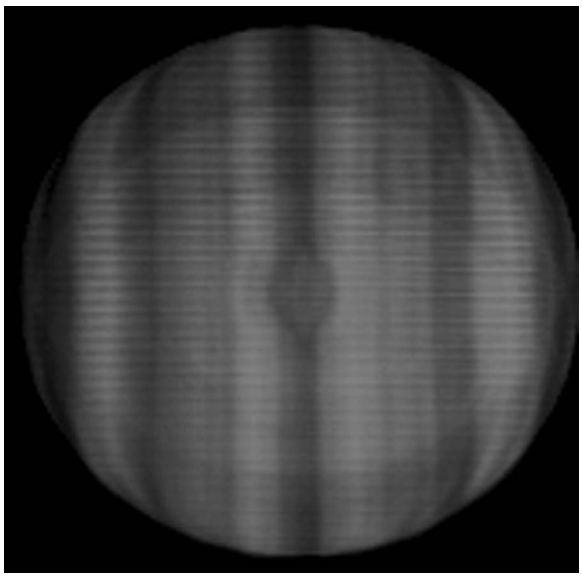
used for measuring the defects on the QPM by utilizing the local distance of the lens and the curvature radii of the surface under test in an interference plane. The wavelength of a He–Ne laser ($\lambda = 632.8$ nm) was used as a reference. The deformations on the mirror were measured using the software IRAF (developed for astronomical purposes) by applying a Fourier algorithm to the interferogram.[14] The first order of the obtained Fourier transform is filtered using an elliptical function, and the inverse Fourier transformation is applied, generating a wrapped phase. In Fig. 3(c) the height information, or shape of the optical surface, is derived when the phase is unwrapped, and the grayscale is in nanometers. Therefore it is easy to sketch a line on the surface deformations to obtain their maximum and minimum (x,y) coordinates [Fig. 3(d)]. Thus, the depth of hole 1 was measured as $h_1 = 214.64\ \text{nm} \approx \lambda/3$, with a rms of $\Delta h_1 = 10.5$ nm. For hole 2, $h_2 = 56.85\ \text{nm} \approx \lambda/11$, with a rms of $\Delta h_2 = 4.71$ nm. And finally, for hole 3, $h_3 = 34.74\ \text{nm} \approx \lambda/18$, with a rms of $\Delta h_3 = 2.85$ nm. In Fig. 3(e) a zooming of the Foucaultgram image of the surface under test is shown. Here the three deformations on the mirror can be observed.

Some Ronchigrams were obtained for the same surface deformations, displaying on the LCD a ruling of 50 lines per inch. It was noticed that by the lateral displacement of the ruling contained on the LCD, hole 1 is presented as a small spot in Fig. 4(a), 4(c), 4(d), and 4(f). Hole 2 is barely observed in Fig. 4(c) and 4(f), and hole 3 is not evident. Video 1 shows the lateral shifting of a classical Ronchi ruling in the Rochi test.

In Fig. 5, the resolution in the Ronchi test has been increased by displaying on the LCD a ruling of 86 lines per



Video 1 Lateral shifting of a classical Ronchi ruling in the Ronchi test. [URL: http://dx.doi.org/10.1117/1.3072956.1]



Video 2 Lateral shifting of a variable frequency ruling in the Ronchi test. [URL: http://dx.doi.org/10.1117/1.3072956.2]

inch (one line=0.147 mm). We observe blurred Ronchigrams, and therefore the deformations on the mirror can be confused. Only is hole 1 evident in all Ronchigrams; hole 2 and hole 3 are not evident even when the LCD is laterally shifted.

In Fig. 6, the resolution in the Ronchi test is again increased by displaying on the LCD a ruling of 100 lines per inch (one line=0.127 mm). As can be seen, hole 1 alone is evident when the LCD is laterally shifted. Thus we have similar results to those obtained in Fig. 5.

Also, one Ronchi ruling with 133 lines per inch (one line=0.095 nm) and another with 170 lines per inch (one lines=0.074 mm) were displayed on the LCD. In Fig. 7(a) and 7(b) are shown the corresponding Ronchigrams. In this figure, only two images are presented, because lateral displacement of the LCD always generated the same image in the detection plane. As has been shown in Fig. 5–7, the dynamic range of detection of the Ronchi test has been increased by iteratively changing the number of lines per millimeter in the rulings displayed.

The dynamic range of a new Ronchi ruling is shown in Fig. 8 when three different frequencies of rulings are combined in a single ruling (substructured ruling) using the LCD. The rulings used in these Ronchigrams were 50, 86, and 133 lines per inch. As a result, the small details of hole 1 can be viewed in Fig. 8(a)–8(f). Hole 2 can be seen as a small spot in Fig. 8(a) and 8(c)–8(f). In Fig. 8(b) hole 2 is not seen; however, in Fig. 8(c) it is visible. Video 2 shows the lateral shifting of variable frequency ruling in the Ronchi test.

By means of the lateral shift of the LCD, hole 3 can be seen in Fig. 8(e) and 8(f). This occurs when a fine line of the variable-frequency ruling is located on hole 3.

Other tests were realized by combining rulings of 100, 133, and 170 lines per inch. As can be seen in Fig. 9, hole 2 and hole 3 were lost in blurred Ronchigrams, whereas hole 1 is seen when the ruling is laterally shifted. This indicates that if we work with a density $\geqslant$170 lines per inch, then overlap of the different orders of the ruling occurs when the LCD is used as a ruling.

6 Conclusions

In this work, we have introduced an alternative method that uses a variable-frequency ruling for optical testing. In order to show the dynamic range of detection of the Ronchi test, an optical surface was tested and the defects in the surface were observed when the variable-frequency ruling was laterally shifted. With the variable-frequency ruling it was possible to observe deformations $\geqslant\lambda/11$. Finally, the effects of pixelation produced by the LCD were reduced by moving the LCD far beyond the curvature radii.

The effects of diffraction produced by the LCD in the experimental setup were not considered in our analysis. However, a larger dynamic range of detection could be established by means of the implemented variable-frequency ruling.

Acknowledgments

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References

1. A. Cornejo-Rodríguez, "Ronchi test," Chap. 9 in *Optical Shop Testing*, D. Malacara, Ed., pp. 321–357, John Wiley and Sons (1992).
2. K. Creath and J. C. Wyant, "Moiré and fringe projection techniques," Chap. 16 in *Optical shop testing*, D. Malacara, Ed., pp. 653–668, John Wiley and Sons (1992).
3. M. Mora-González and N. Alcalá-Ochoa, "The Ronchi test with a LCD grating," *Opt. Commun.* **191**, 203–207 (2001).
4. N. Alcalá-Ochoa, M. Mora González, and F. Mendoza Santoyo, "Flatness measurement by a grazing Ronchi test," *Opt. Express* **11** (18), 2177–2182 (2003).
5. J. Castro-Ramos, S. Vázquez-Montiel, and A. Padilla-Vivanco, "Phase shifting interferometry by using a LCD and bironchi test," in *5th Iberoamerican Meeting on Optics and 8th Latin American Meeting on Optics, Lasers, and Their Applications*, A. Marcano and O. J. L. Paz, Eds., *Proc. SPIE* **5622**.
6. M. V. R. K. Murty and A. Cornejo, "Sharpening the fringes in the Ronchi test," *Appl. Opt.* **12**(10), 2230–2231 (1973).
7. A. Cornejo-Rodríguez, F. Granados-Agustín, and Y. Luna-Zayas, "The Ronchi test and the use of structured gratings for sharpening the fringes," *Laser Science XXII, Frontiers in Optics, Optical Fabrication and Testing (OF&T) Topical Meeting*, OSA (2006).
8. R. H. Katyl, "Moiré screens coded with pseudo-random sequences," *Appl. Opt.* **11**, 2278–2285 (1972).
9. A. Cornejo, H. Altamirano, and M. V. R. K. Murty, "Experimental results in the sharpening of the fringes in the Ronchi test," *Bol. Inst. Tonantzintla* **2**(4), 313–315 (1978).
10. M. Mora-González and N. Acalá-Ochoa, "Sinusoidal liquid crystal display grating in the Ronchi test," *Opt. Eng.* **42**(6), 1725–1729 (2003).
11. M. Fernandez Guasti, A. Meléndez Cobarrubias, F. J. Renero Carrillo, and A. Cornejo Rodríguez, "LCD pixel shape and far-field diffraction patterns," *Optik (Jena)* **116**, 265–269 (2005).
12. C.-W. Liang and J. Sasian, "Geometrical optics modeling of the grating-slit test," *Opt. Express* **15**(4), 1738–1744 (2007).
13. E. Luna-Aguilar, A. Cornejo-Rodríguez, and A. Cordero-Dávila, "Pruebanula de Ronchi-Hartmann," *Rev. Mex. Fis.* **38**(1), 150–161 (1992).
14. M. Takeda, I. Hideki, and K. Seiji, "Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry," *J. Opt. Soc. Am.* **72**, 156–160 (1982).

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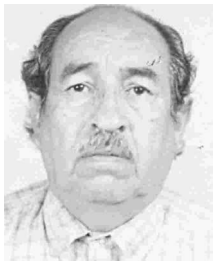

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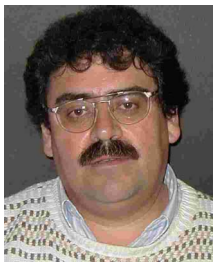

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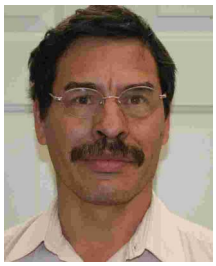

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