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Interferometric Method of Measuring Plotter Distortion

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In this letter an interferometric method of measuring plotter distortion is described. A common method of measuring plotter distortion is to draw a known pattern, such as straight lines, and scan this pattern with a microdensitometer. This is a precise method of measuring distortion; however, it is a time consuming process; and it gives distortion only along the microdensitometer scan lines. The technique described below gives a contour map for the whole plot showing lines of constant distortion in a particular direction. By combining two contour maps for distortion in two orthogonal directions, the distortion in any arbitrary direction can be found. If the plotter distortion is repeatable and the plotter is computer controlled, once the distortion is known it can be eliminated as described by Fercher et al.[1,2]

As will now be shown, if a plotter draws straight lines the plot can be thought of as a hologram produced by interfering two plane wavefronts. The plotter distortion produces the same effect on the plot as aberration in one of the plane wavefronts would produce on the hologram. If a plotter were to draw perfectly straight lines perpendicular to the x direction, the equation of. the straight lines would be $(x/\Delta x) = M$, where Δx is the line spacing and M is an integer, 0, 1, 2, and so forth. Because of plotter distortion, the lines are never perfectly straight. Let the distortion in the x direction be $\delta x(x, y)$. Thus a point that should have the x coordinate x will have the x coordinate $x + \delta x(x, y)$. Therefore, the equation of the lines drawn by the plotter will be

$$[x/(\Delta x)] + \{[\delta x(x, y)]/(\Delta x)\} = M. \qquad (1)$$

Now consider the interference pattern (or hologram) formed by interfering two wavefronts. If a tilted plane wave, which can be represented as $e^{-ikx\sin\theta}$, where $k = 2\pi/\lambda$, and λ is the wavelength, and an aberrated plane wave represented as $\exp[ik\,\phi(x, y)]$ are interfered, a bright fringe is obtained every time the phase difference between the two interfering wavefronts is a multiple of 2π. That is, a fringe of order M is obtained when $kx\sin\theta + k\,\phi(x, y) = 2\pi M$. Dividing through by 2π yields

$$\frac{x\sin\theta}{\lambda} + \frac{\phi(x, y)}{\lambda} = M. \qquad (2)$$

Equations (1) and (2) show that the plot of distorted straight lines can be thought of as a hologram made by interfering a tilted plane wave with an aberrated plane wave. A distortion 6x equal to the average line spacing, Ax, corresponds to one wave of aberration. For example, if the plot lines are spaced 500 μ, a distortion of 500 μ corresponds to one wave of aberration. The above results can also be considered in terms of detour phase as previously described in the literature.[3,4]

If the plot is recorded on photographic film and illuminated with a plane wave, several diffracted orders will be produced, just as would be produced by a diffraction grating or hologram. The first order will be an aberrated plane wave. The aberration function in units of waves is equal to $[\delta x(x, y)/\Delta x]$. As for a regular hologram, the second order will have twice as much aberration, the third order will have three times as much, etc[5,6,7] In general the Nth diffracted order will have N times as much aberration as the first order. If the Nth diffracted order is interfered with a plane wave, the resulting interferogram gives plotter distortion in the same manner as Twyman Green interferometers give wavefront aberration.

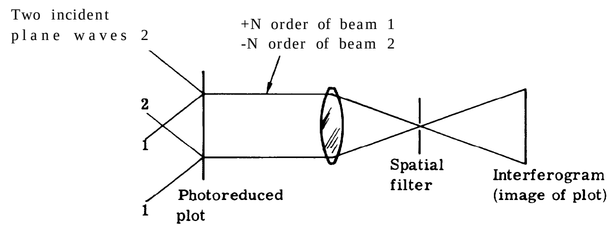


Fig. 1. Experimental setup for testing plot.

Figure 1 shows a convenient setup for testing a plot. Either the plot or a photo reduced version of the plot is illuminated with two plane wavefronts. The plot is reimaged as shown. A spatial filter (small aperture) is placed in the focal plane of the reimaging lens. The two plane wavefronts are incident upon the plot at the appropriate angle such that the +N order as produced by beam 1 and the -N order as produced by beam 2 pass thru the spatial filter. The number of fringes in the resulting interferogram is selected by adjusting the tilt of the two illuminating plane waves. If the lines drawn by the plotter are spaced a distance Ax, a fringe error in the interferogram corresponds to a distortion error of an integer multiple of $\Delta x/2N$ in the plot. In general, any two diffracted orders can be interfered. It is convenient to pick ±N, because, if the two incident plane waves have the same intensity, the two interfering wavefronts have the same intensity and good contrast interference fringes are obtained.

If the spatial filter shown in Fig. 1 is removed from the setup, the shape of the fringes in the interferogram is unchanged; however the contrast of the fringes is reduced. The interferogram obtained in this case is the moire, between the plot and the interference fringes formed by interfering plane waves 1 and 2.

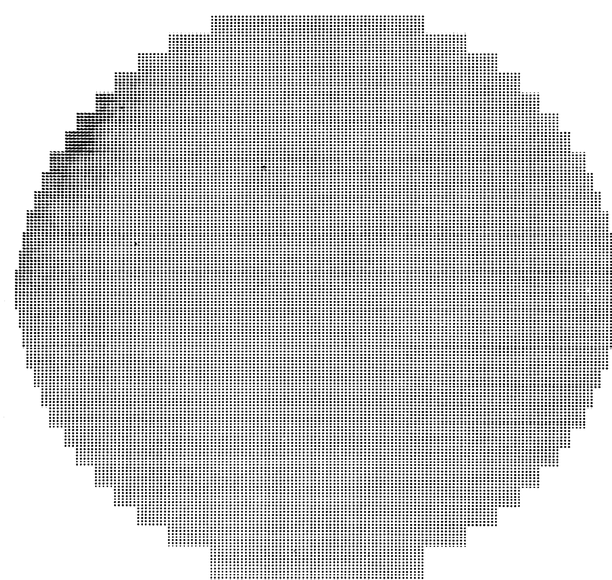
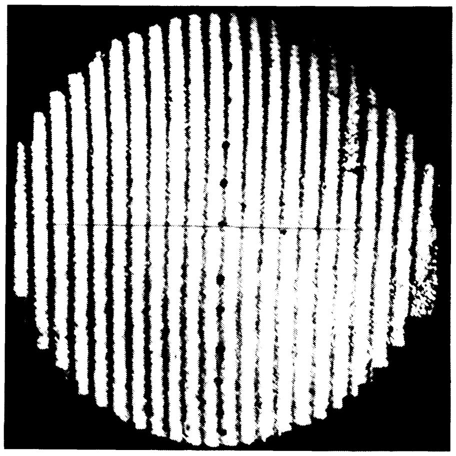


Fig. 2. Laser beam recorder plot.



Error in vertical lines

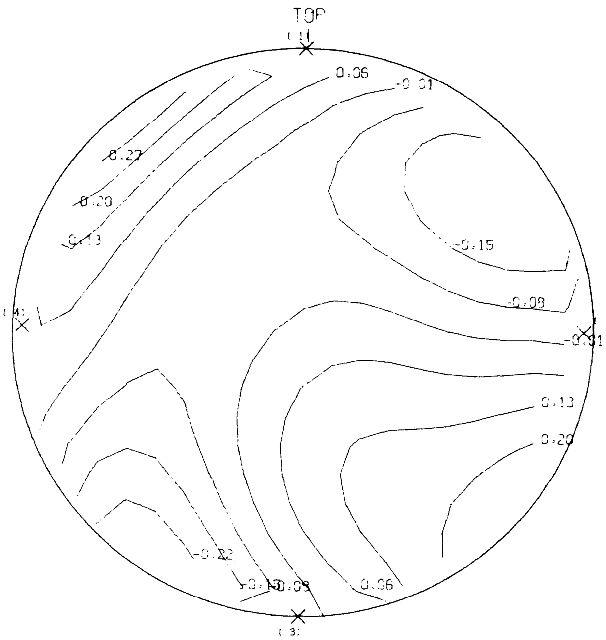


Fig. 3.
Distortion in x direction (200 μ m per wave).
Top: Error in vertical lines.
Bottom: error in vertical lines; peak-to-peak,
error = 0.69 wave = 138 μ m; RMS error = 0.13 wave = 26 μ m.

A good feature of the experimental setup shown in Fig. 1 is that if the plot is recorded on a photographic plate, the plate need not be extremely flat. If the two plane wavefronts are incident on the emulsion side of the plate, the two diffraction orders of interest will both see the same thickness variations. Thus, thickness variations in the plate will not affect the final interferogram.

It should be noted that if a photo reduced version of the plot is used in the test setup, instead of the actual plot, the combined distortion produced by both the plotter and the photo reduction lens is being measured. This suggests using this technique for measuring lens distortion. If a straight line pattern having either essentially zero distortion, or at least known distortion, is photographed and the resulting transparency is placed in this setup, the distortion produced by the photo reduction lens can be obtained.

Figure 2 shows a plot drawn by a laser beam recorder. The diameter of the plot was approximately 20 cm and the spacing of the lines or dots was approximately 1200 μ m. The plot was photoreduced to a diameter of 2 cm. A two-dimensional dot pattern was drawn so distortion in both the horizontal and the vertical direction could be measured. The vertical lines give distortion in the horizontal direction, and the horizontal lines give distortion in the vertical direction.

Figure 3 shows results obtained measuring distortion in the x direction. The spatial filter shown in Fig. 1 was positioned to pass diffraction orders produced by the vertical lines. The tilt between the two incident plane waves was adjusted to produce the interference fringes shown. The fringe positions were measured and this data was put into a computer, which took out the tilt to obtain the contour map shown. The lines in the contour map are lines of constant distortion in the x direction. Since the lines on the original plot were spaced 1200 μ and ±3rd diffraction orders were interfered, one fringe error in the interferogram corresponds to a distortion error of 1200 divided by 6, or 200 μ. By combining the results shown in Fig. 3 with similar results obtained for distortion in the y direction, the distortion in any desired direction can be found. If the plotter distortion is repeatable and the plotter is computer controlled, once the distortion is determined it can be eliminated.

Figure 4 shows a very interesting distortion error. The vertical lines drawn by the plotter in some cases were displaced horizontally about 80 μ from the correct position. Since the lines drawn by the plotter were spaced 1200 μ, it was very difficult to see the 80–μ horizontal displacement in the plot. However, by using the technique described in this paper the error became very obvious, as shown in the figure. In summary, this letter describes an interferometric method of measuring plotter distortion in which an interferogram is obtained giving plotter distortion in the same manner as Twyman Green interferograms give wavefront aberrations. Each interferogram gives dis-

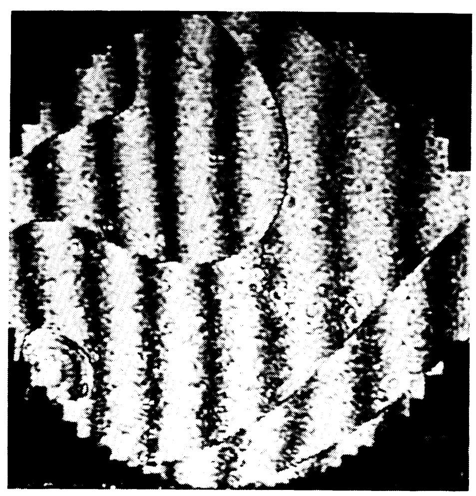


Fig. 4. Error in laser beam recorder lines (200 μ m per fringe).

tortion in a particular direction. From two interferograms, giving distortion in two orthogonal directions, the distortion in any desired direction can be obtained. The technique can also be used to measure lens distortion.

The authors are indebted to the referee who pointed out Refs. 1 and 2.

References

1. A. F. Fercher and M. Kriese, Optik 35, 168(l972).
2. A. F. Fercher, P. Skalicky, and J. Tomiser, Opt. Laser Tech. 5, 75(1973).
3. B. R. Brown and A. W. Lohmann, Appl. Opt. 5,967(1966).
4. A. W. Lohmann and D. P. Paris, Appl. Opt. 6,1739(1967).
5. O. Bryngdahl and A. W. Lohmann, J. Opt. Soc. Am. 58, 141(1968).
6. O. Bryngdahl, J. Opt. Soc. Am. 59,142(1969).
7. K. Matsumato and M. Takashima, J. Opt. Soc. Am. 60, 30(1970).