# Techniques of Optical Spatial Filtering Applied to the Processing of Moiré-fringe Patterns

A coherent optical system which forms the image of an object in two stages is described. Spatial filtering is performed at the first-image plane

by Fu-pen Chiang

## Introduction

The process of optical spatial filtering in a coherent light system alters the input signal (e.g., the light disturbance transmitted through a moiré pattern) by placing spatial filters along the optical path of the light in such a way that the output signal is modified in a prespecified way. Filtering can be categorized into amplitude, phase and complex depending upon whether it is performed to the amplitude, phase or both, respectively, of the light disturbance. Although spatial filtering is not new, major advancements have been made only recently, notably by Vander Lugt[1] and Cutrona,[2] among others.

Since many techniques in experimental stress analysis are optical methods, it is natural to find applications of spatial filtering to the processing of experimental data. Examples of contributions along this direction are the works of de Haas and Loof,[3] Post,[4, 5] Sciammarella,[6] and Holister.[7] Presented herein are some techniques of amplitude filtering applied to the process of moiré patterns.

*Fu-pen Chiang is Assistant Professor, Department of Mechanics, State University of New York at Stony Brook, N. Y.*

*Paper was presented at 1969 SESA Spring Meeting held in Philadelphia, Pa., on May 13–16.*

## Basic Optical Arrangement

The basic optical arrangement used in this note is a two-dimensional optical filtering system shown in Fig. 1, in which the object to be filtered is placed

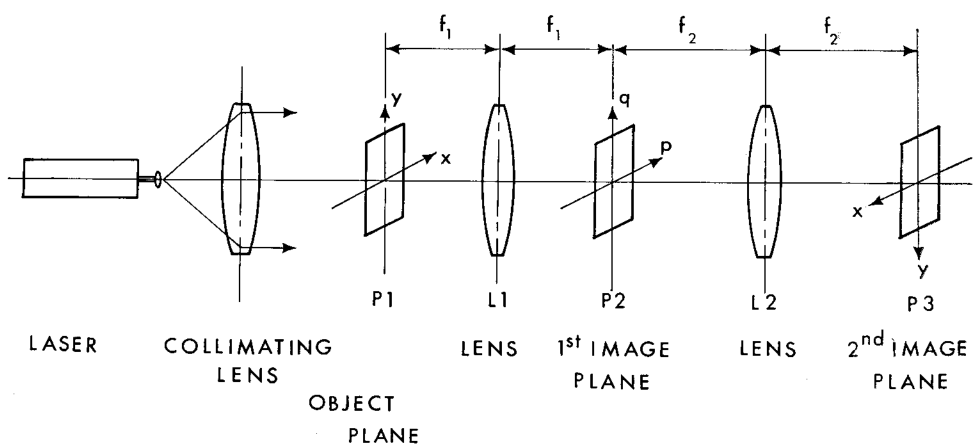



Fig. 1—Arrangement of the components of an optical spatial filtering system

at plane $P_1$, filtering is performed at plane $P_2$, and the final image formed in plane $P_3$. If $f(x,y)$ denotes the complex amplitude of the light flux at plane $P_1$ front focal plane of lens $L_1$), the complex amplitude of the light flux at plane $P_2$, i.e., the diffraction spectrum of $f(x,y)$ is expressed by the Fourier transform of $f(x,y)$, i.e.,

$$F(p,q) = \iint_{-\infty}^{\infty} f(x,y)e^{i(px+qy)}dxdy \qquad (1)$$

in which $(x,y)$ and $(p,q)$ are the coordinates at the front and back focal planes of lens $L_1$, respectively. Since different signals have different Fourier transforms and, thus, different spatial distributions of their diffraction spectrum, eq (1) renders itself as the basis for spatial filtering. Indeed, if a certain signal from a moiré pattern is not wanted on the final picture, it can be eliminated by preventing its diffraction spectrum from entering the second imaging lens, and if a certain signal has too much a share of the total energy distribution, its energy can be reduced at the spectrum plane ($P_2$) by placing neutral density filters along its optical path. As a demonstration of diffraction phenomena and for use in the following section, the diffraction spectra of a 300-lpi one-directional grating and a 1000-lpi crossed grating are shown in Fig. 2.

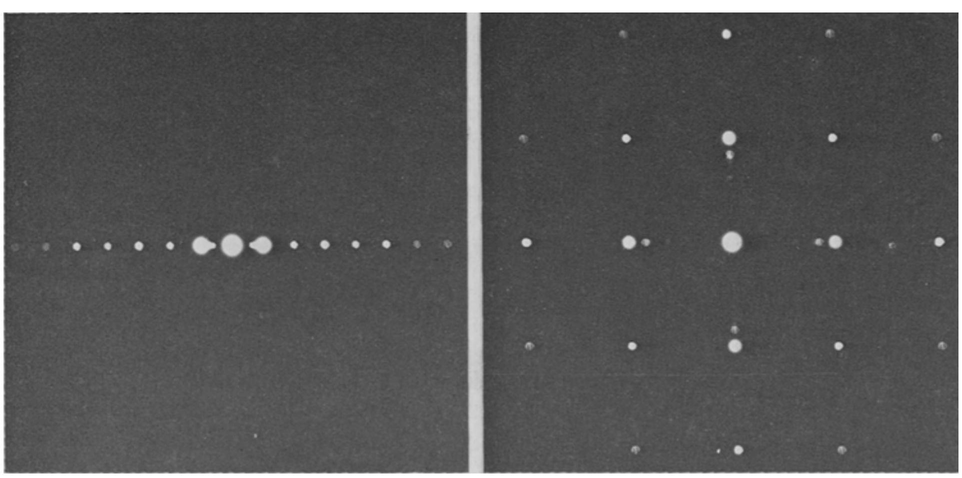
## Applications of Spatial Filtering

### *Separation of u-field and v-field Moiré Patterns*

In applying the moiré method, both the *u*-field moiré and the *v*-field moiré are required for a complete determination of the state of strain of a plane model. They are usually obtained by rotating the master grating through an angle of 90 deg. However, as pointed out by Post,[8] an inaccurate rotation will cause serious shear errors and it is advisable to form both *u*- and *v*-field patterns simultaneously by employing a crossed grating as master. For this technique it would be desirable sometimes to separate the two patterns for reducing the possible confusion caused by the tangling of two sets of fringes. The following methods are presented for this purpose.

METHOD A—If a transparent model printed with a crossed grating is placed at plane $P_1$ in Fig. 1, its diffraction spectrum will be displayed at plane $P_2$ with a configuration similar to the one shown in Fig. 2(b), consisting of a two-dimensional array of orders. This diffraction spectrum is then collected by lens $L_2$ to form an image of the model grating in plane $P_3$. If an identical master grating is placed at plane $P_3$, it will interfere with the image of the model grating upon deformation to form a moiré pattern. This is similar to the conventional way of forming moiré patterns at the back of a camera. However, if a mask is placed at plane $P_2$ in such a way that only *a horizontal array* of the orders of the diffraction spectrum is allowed to pass through the optical system, the *v*-field moiré fringes will be completely eliminated from the image plane $P_3$. This is because now the effective diffraction spectrum is equivalent to that of a one-directional line grating as shown in Fig. 2(a). Similarly, if this mask is turned 90 deg so that only a *vertical* array of orders is allowed to go through the system, the *u*-field moiré fringes will be eliminated from the image plane. An example is given in Fig. 3 where (a) is the pattern before filtering and (b) and (c) are the patterns after filtering. The mask is made of a piece of black paper with a cut-out window having a width slightly larger than the diameter of the dots and a length long enough to let at least two neighboring orders pass through.

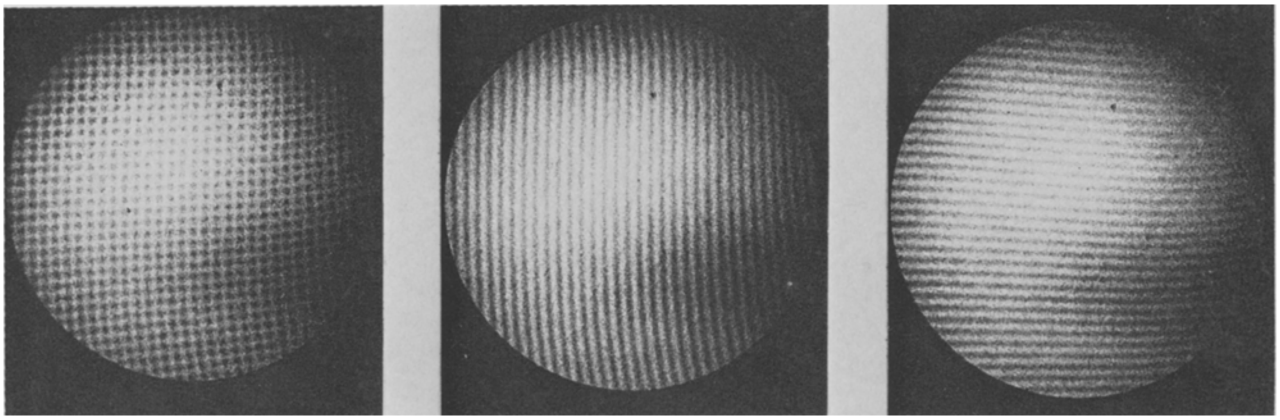
METHOD B—If the model is opaque or the loading apparatus for the model is such that it is impossible to be put into the optical system, then the following method should be applied: the crossed-moiré pattern is first formed by the conventional method and



(a) 300-lpi one-directional grating

(b) 1000-lpi crossed grating

Fig. 2—Photographs of the diffraction spectra of gratings



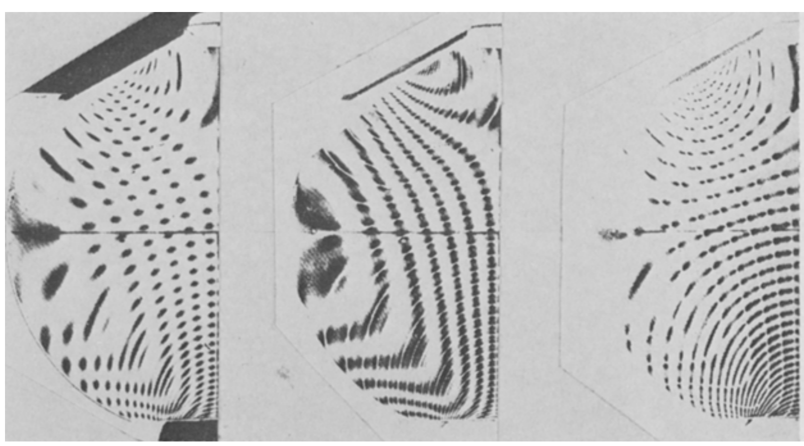
(a) Cross-moiré-fringe pattern (b) U-family (c) V-family

Fig. 3—Separation of moiré-fringe families with master grating at second image plane

recorded on a piece of film together with the crossed grating lines. This film (negative) is then placed into the optical system at plane $P_1$ and the filtering process followed. The diffraction spectrum is of the same appearance as that of a regular crossed grating, except that the information contained in each order has been modulated by the moiré fringes. While the (0,0) order contains both $u$-field and $v$-field fringes, any one order along the central horizontal array of orders contains only $u$-field fringes and any one order along the central vertical array of orders contains only $v$-field fringes. Therefore, if a mask with a hole is placed at plane $P_2$ to let one order along the central horizontal (or vertical) array, except the (0,0) order, go through the optical system, only the $u$- (or $v$-) field fringes will be seen at plane $P_3$. An example is given in Fig. 4 where (a) is the original crossed-moiré pattern and (b) and (c) are the filtered versions of the $u$-field and $v$-field fringes, respectively. The fringes thus obtained are not continuous and the discontinuities occur at the places where fringes belonging to the other field have been eliminated. However, the overall features of the patterns are preserved and they are now less confusing to analyze than the original crossed-moiré pattern.

*Filtering of Noises*

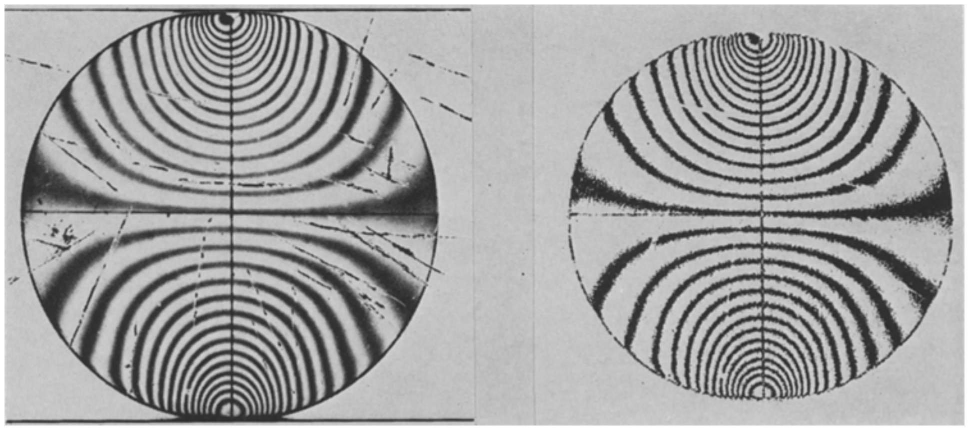
Another application of spatial filtering is the suppression of noises from moiré patterns. For noises to be filterable, they should not have the same spatial frequencies as that of the moiré fringes. If they do not, the diffraction spectrum of noises and that of moiré will occupy different positions at the transform plane $P_2$. A mask can then be made in such a way that only the spectrum of moiré is allowed to go through the optical system, and noises are thus eliminated from the final picture. An example is given in Fig. 5 in which a badly scratched moiré pattern is shown corrected by the process of filtering. It is obtained by letting a diffraction order, least entangled with the spectrum of the noises, go through the optical system. Not all the noises are eliminated by the filtering, as can be seen from the picture. However, the quality is definitely improved.



(a) Cross-fringe pattern (b) U-family (c) V-family

Fig. 4—Separation of moiré-fringe families after the cross-fringe pattern is recorded on film

Fig. 5—Noise suppression by optical spatial filtering



(a) Before (b) After

*Contrast Improvement*

In 1966, de Haas and Loof[3] used the Shlieren setup to improve the contrast of moiré patterns obtained by the Lightenberg method.[9, 10] They claimed that, in order to apply their technique to moiré patterns formed by plane gratings, it would be necessary to introduce a large amount of mismatch to diffract the light.

It is not necessary to introduce mismatch if the background grating can be recorded on film together with the moiré pattern. The diffraction of light is then, of course, achieved by the grating. An example of contrast improvement is given in Fig. 6, in which (a) is the pattern before and (b) after filtering. No mismatch was introduced in the pattern. Furthermore, even if the grating is not resolved by the film, filtering is still possible by using a highly coherent light source (e.g., laser) and enlarging the diffraction spectrum. Filtering can then be done by placing neutral-density filters to reduce the energy of the undiffracted light.

## Conclusion

It is seen that with the optical spatial-filtering system described in the note, many filtering operations can be performed either to facilitate the interpretation or to improve the quality of moiré patterns.

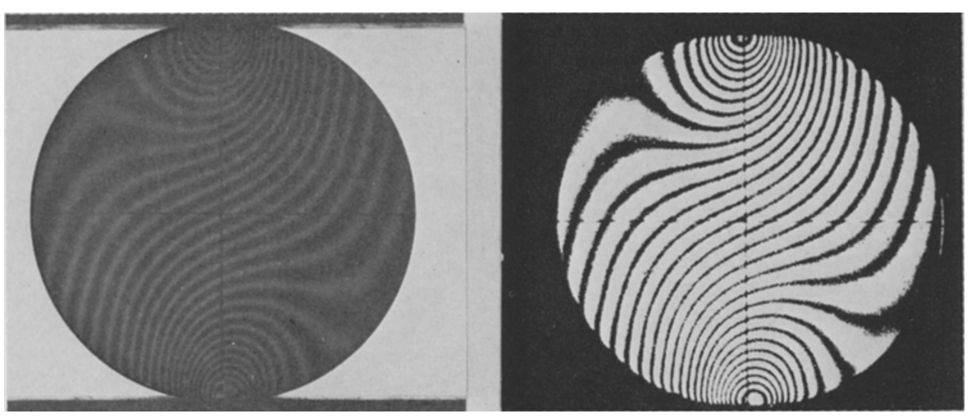
*Acknowledgment*

The author wishes to acknowledge gratefully the financial support of the National Science Foundation through an Engineering Research Initiation Grant #GK-3039.

*References*

1. Vander Lugt, A., "Signal Detection for Complex Spatial Filtering," IEEE Trans. Inform. Theory, IT-10, (2) (April 1964).
2. Cutrona, L. J., Recent Developments in Coherent Optical Technology, Optical and Electro-Optical Information Processing, edited by Tippett, Clapp, Berkowitz and Kaestor, Chpt. 6, MIT Press, Cambridge, Mass. (1965).
3. de Haas, H. M. and Loof, H. W., "An Optical Method to Facilitate the Interpretation of Moiré Pictures," VDI-Berichte, Nr. 102, Experimentelle Spannungsanlyse, Berlin (1966).
4. Post, D., "New Optical Methods of Moiré-fringe Multiplication," EXPERIMENTAL MECHANICS, 8(2), (1968).
5. Post, D., "Analysis of Moiré Fringe Multiplication Phenomena," Appl. Opt., 6 (11) (1967).
6. Sciammarella, C. A., "Moiré-fringe Multiplication by Wave-front Reconstruction," EXPERIMENTAL MECHANICS, 9 (4), (1969).
7. Holister, G. S., "Moiré Method of Surface Strain Measurement," Engineer (Jan. 27, 1967).
8. Post, D., "The Moiré Grid-analyzer Method for Strain Analysis," EXPERIMENTAL MECHANICS, 5 (11), (1965).
9. Beranek, W. J., "Rapid Interpretation of Moiré Photographs," EXPERIMENTAL MECHANICS, 8 (5), (1968).
10. Ligtenberg, F. K., "The Moiré Method," Proc. SESA, XII (2) (1955).

Fig. 6—Photographs showing contrast improvements of a moiré-fringe pattern



(a) Before filtering (b) After filtering