Optical Methods in Experimental Mechanics

Part 21: Shadow Moiré

REVIEW AND PURPOSE

The previous two articles of this series demonstrated how the geometric moiré effect is used to measure in-plane deformations and rotations.

This article describes a technique for using a variant of geometric moiré to measure out-of-plane displacement and to map the absolute contours of three-dimensional objects. It is called "shadow moiré."

WHAT IS SHADOW MOIRÉ?

The shadow method of geometric moiré uses the superimposition of a master grating and its own shadow. The fringes are loci of constant out-of-plane elevation, so they yield a contour map of the object being studied. In studies of deformable bodies, the method can be used to measure out-of-plane displacements or changes in displacement. Shadow moiré is very simple to implement, and it requires no sophisticated apparatus. The resulting fringe patterns are easily recorded and interpreted.

Shadow moiré pattern showing buckling mode of elliptical graphite/epoxy [45°]$_8$ composite panel with clamped edges. From Singhatanadgid, P., and Tuttle, M., "Buckling of Elliptical Anisotropic Plates Subjected to Biaxial Loading," Proceedings of 2000 IX SEM International Congress on Experimental Mechanics. Photo courtesy of Dr. Mark Tuttle, Chair of Mechanical Engineering, University of Washington.

SHADOW MOIRÉ DEMONSTRATIONS

As with other moiré phenomena, shadow moiré is easily seen in the world around us. It is observed when sheer fabric, netting, or screen material is lain over a curved surface and illuminated with a lamp or sunlight. Classroom demonstrations of shadow moiré are effectively accomplished using gratings that are laser printed on transparencies. A grating is placed in front of a convoluted object, and illumination as from an off-axis projector is passed through the grating and onto the object.

An effective alternate approach is to create a computer simulation using software that allows projection of shadows from an illuminated object and that also allows rotation of the setup so it can be viewed from different vantage points. Most graphics programs do not have this capability. However, a suitable demonstration can be constructed using CAD software such as Unigraphics®, and the result can be recorded as a computer video for classroom showing. A distinct advantage is that the grating spacing, the position of the light source, the nature of the grating shadow, and the vantage point are easily varied. The moiré interaction of the grating with the monitor raster is a distraction, as is usual when moiré work is done on a computer. The pictures below were extracted from such a simulation. The first is an off-axis top view that shows how light is passed through

Shadow moiré:
- *appears when a grating is superimposed with its own shadow,*
- *yields fringes that are loci of points of constant separation between the master grating and the specimen,*
- *provides a contour map of the specimen,*
- *can be used to measure out-of-plane deformation,*
- *is easily implemented.*

Shadow moiré:
- *is readily apparent in everyday life,*
- *can be created by placing screen material adjacent to a curved surface and illuminating the combination,*
- *is easily demonstrated using laser-printed grating transparencies.*

Editor's Note: Optical Methods—Back to Basics, *is organized by ET Senior Technical Editor, Kristin Zimmerman, General Motors, and written by Prof. Gary Cloud of Michigan State University in East Lansing, MI. The series began by introducing the nature and description of light and will evolve, with each issue, into topics ranging from diffraction through phase-shifting interferometries. The intent is to keep the series educationally focused by coupling text with illustrative photos and diagrams that can be used by practitioners in the classroom, as well as in industry. Unless otherwise noted, the graphics in this series were created by the author.*

The series author, Prof. Gary Cloud (SEM fellow), is internationally known for his work in optical measurement methods and for his book, Optical Methods of Engineering Analysis.

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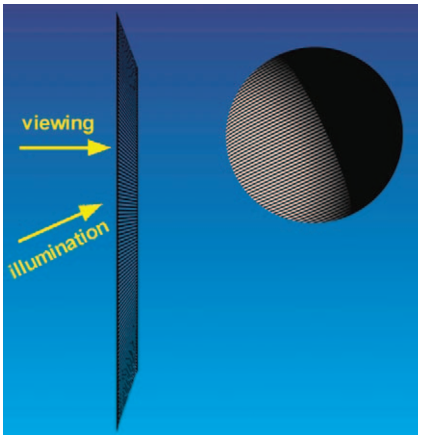
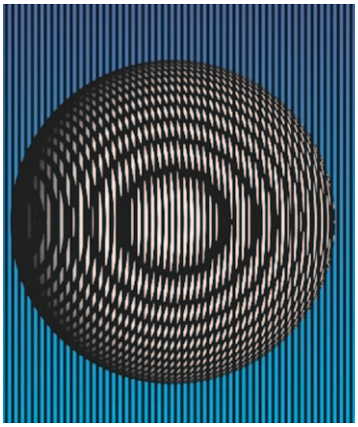
a master grating so as to create shadows of the grating lines on the object to be studied, in this case a simple sphere. To see the moiré effect, the object is viewed through the master grating along an axis that differs from the illumination axis, as shown.

Shadow moiré simulations can be generated using CAD software that incorporates a shadow feature.



The second picture shows the resulting moiré fringe pattern from the viewer's vantage point. Dark fringe areas are seen wherever dark shadows of the grating are aligned with gaps in the master grating—there is no light to get through the gap. Light fringes form where light areas of the shadow pattern line up with the spaces in the master. The result is a fringe pattern, as usual. Coarse gratings were used for these simulations to reduce aliasing problems, so the individual grating lines appear in the fringe patterns.

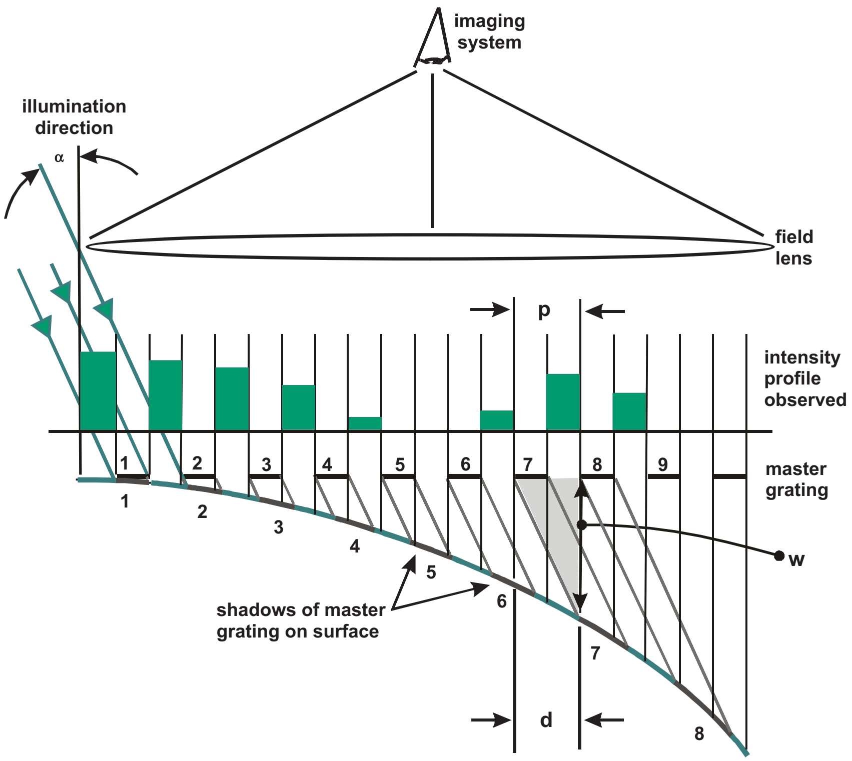


Short motion pictures of two Unigraphics simulations may be downloaded from the web using the following addresses: www.egr.msu.edu/~cloud/3_views_fine_sphere.mpg and www.egr.msu.edu/~cloud/3_views_coarse_sphere.mpg. The simulations, the films, and the pictures presented above were prepared by Mr. Jeffrey Bosscher while a student at Michigan State University. File sizes are about 2 Mb.

ANALYSIS OF SHADOW MOIRÉ

In order to understand the creation of fringes and to be able to interpret them quantitatively, consider the optical system shown in the conceptual sketch below.

A master grating of pitch p is placed in front of a curved object that has a light-colored nonreflective surface. The combination is illuminated with a collimated beam at incidence angle α. Observation is along the normal to the master grating by use of a field lens that converges the light scattered back through the master grating to the location of a camera or an eye that is focused on the object.



The incident illumination creates on the surface of the specimen a shadow of the grating. The shadows of the grating lines are elongated on the specimen by a factor that depends on the incidence angle and the inclination of the surface, and they are shifted laterally by an amount d that depends on the incidence angle and the distance w from the master grating to the specimen.

The specimen with its shadow pattern is observed through the spaces in the master grating. There are some locations in the composite view where the light areas of the shadows line up with the spaces between the lines of the master, and these areas will appear light. In other areas, the dark shadows will be aligned with the spaces in the master, and these areas will appear dark. The sketch shows slightly more than one complete cycle of this effect, from light to dark, back to light, and going back to dark again. Note that the elongations of lines in the shadow do not affect the composite picture if viewing is along the normal. In practice, fine gratings are used, the imaging system acts as a low-pass filter, the light areas blend to form smooth light fringes, and the dark areas blend into dark fringes. The individual grating lines are usually not rendered by the imaging system unless coarse gratings are used, as is the case with the pictures presented above.

The relationship between fringe order and master-specimen separation distance is derived in a manner similar to that used for in-plane moiré in Part 10 of this series. The figure shows that a complete fringe cycle takes place when, in this case, the shadows of seven grating lines are spread over the expanse of eight lines in the original grating. In general terms, the shadows of m grating lines are spread over the extent of $m \pm 1$ lines of the master grating for one fringe order. Let w be the change in the gap between master grating and specimen over the same expanse. Examination of the gray triangle in the figure shows that, for one fringe cycle, the lateral shift d of a line equals the pitch p, so:

$$\frac{[(m+1)-m]p}{w} = \tan\alpha$$

In the shadow of the master grating that appears on the specimen, for a given angle of illumination:

- *the shadow lines are elongated by the inclination of the specimen,*
- *the shadow lines are shifted laterally by a factor depending on the distance from the master grating to the specimen.*

When the shadow of the master grating is viewed through the master grating:

- *some light areas of the shadow will coincide with spaces in the master to create a light area in the image,*
- *some light areas of the shadow will be blocked by lines in the master to create a dark area,*
- *dark areas of the shadow will be dark in any case,*
- *the light areas blend together to form light fringes,*
- *the dark areas blend to form dark fringes.*

In the image, one fringe cycle appears when m grating shadows are elongated to fill the space of m ± 1 lines of the master.

In more useful form, the gap corresponding to one fringe order is:

$$w = \frac{p}{\tan \alpha} \tag{20.1}$$

If there are N fringes between two specific locations on the image taken with viewing along the normal, then the change in out-of-plane displacement between those two points is:

$$w = \frac{Np}{\tan \alpha} \tag{20.2}$$

In practice, a field lens might not be used to establish true normal viewing. In that case, Equation 20.2 will not be exactly true except along the central viewing axis. The error will be small if the viewing distance is large compared with the specimen breadth. Similar statements apply if noncollimated light is used for illumination.

If viewing is along some direction other than the normal to the master grating, the sensitivity of the fringes to displacement will be altered. For example, assume that viewing is from a direction opposite to the angle of incidence (clockwise from the viewing axis in the sketch); the effect of the displacement on the fringes will be exaggerated, so sensitivity is increased. The relationship between fringe order and displacement is easily developed for this more general case, with the result:

$$w = \frac{Np}{(\tan \alpha - \tan \beta)} \tag{20.3}$$

where α is the incidence angle, β viewing angle, p grating pitch, N moiré fringe order, and w axial distance from grating plane to specimen.

The signs of the angles are important. If illumination and viewing are from opposite sides of the axis, then β is taken as negative. Equation 20.3 may be used also to estimate the errors caused by noncollimated illumination or if a field lens is not used to establish normal viewing. One merely examines the equation for the range of angles that are imposed by the particular setup.

SOME APPLICATIONS

An interesting application of shadow moiré is in contour mapping of the human body with the aim of detecting asymmetries that indicate certain infirmities such as scoliosis. In some of these biomechanics studies, the necessarily large master grating is fabricated by stretching cords across a framework. That shadow moiré can be used in studies of buckling phenomena is shown in the elegant shadow moiré photograph that appears at the top of this article. Shadow moiré can be used to establish absolute contours of sheet metal stampings or, in quality-control mode, to compare the contour of a manufactured object with that of a master object.

WHAT NEXT

The next article will deal with projection moiré, which seems similar to shadow moiré but which gives different results and has different uses. ■

Simple geometric analysis shows that the gap between specimen and master equals the local fringe order times the grating pitch divided by the tangent of the angle of incidence.

A field lens:

- *is required to establish viewing along the normal for the expanse of the master grating,*
- *can be eliminated with little loss of accuracy if the viewing distance is much larger than the specimen.*

Sensitivity of the method can be increased or lowered by viewing along an inclined axis.

Some applications of shadow moiré include:

- *observation of buckling of panels,*
- *diagnosis of illnesses that affect body conformation,*
- *mapping contours of manufactured parts,*
- *quality control in industry.*