OPTICAL METHODS Back to Basics *by Gary Cloud*

Optical Methods in Experimental Mechanics

Part 23: Reflection Moiré

REVIEW AND PURPOSE

The previous two articles of this series described moiré methods for measuring contours or out-of-plane displacements of an object. The plan was to leave the topic of geometric moiré and begin discussion of laser speckle phenomena and their applications. But there is one more approach, called reflection moiré, that seems deserving of a short article, first because of its unique features and applications and second because of its significance in understanding and extending other methods, including those involving laser speckle. With digital imaging, implementation of the method is even easier than it once was. As usual, only the basic technique is described here and some enhancements are mentioned briefly.

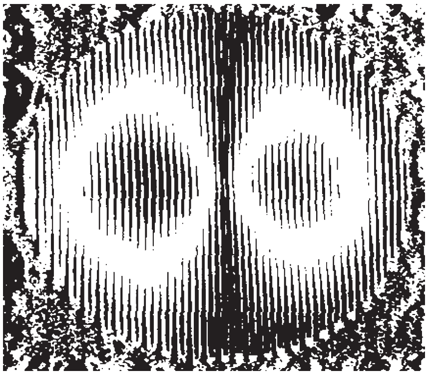
WHAT IS REFLECTION MOIRÉ?

Reflection moiré involves recording the image of a remote grating as it is reflected from the polished surface of a specimen. Superimposition of the reflected grating images from two states of the specimen creates a moiré pattern that yields directly the out-of-plane slope or change of slope of the specimen surface. The method was described by F. K. Ligtenberg in 1954 and subsequently improved and used in structural engineering applications by various investigators. An outstanding feature is that implementation is simple and equipment needs are minimal. It can be applied to very small specimens or scaled up to imposing civil infrastructure components.

The technique seems to have been largely forgotten in recent years, but it has the unique advantage of providing direct observation of slopes and therefore curvatures and bending moments in structural components such as beams, plates, and shells. Experimental techniques that give contour or out-of-plane displacement, including shadow and projection moiré, can also be used to obtain slope and curvature, but differentiation of the primary experimental data, always problematical, is required in those cases. Another reason for being mindful of reflection moiré is that it can help us understand and extend certain other optical methods, notably speckle techniques. There is reason to believe that a method of speckle interferometry that combines advantageous features of reflection moiré and speckle interferometry can be developed as an additional tool in the experimentalist's kit.

ANALYSIS OF REFLECTION MOIRÉ

The sketch below shows in cross section the basic experimental arrangement for reflection moiré measurement of a plate or membrane. The angles and the plate deflection are exaggerated here for clarity. The plate to be studied is polished on the viewing side so as to act as a mirror, and it is mounted in a holder, which provides correct boundary conditions and facility for applying the required load. At distance *d* from the plate is erected a moiré master grating that is well illuminated. Errors are reduced if the grating is curved, but a flat grating is often used, and the



Reflection moiré pattern for a clamped circular plate with a central load obtained using grating generated on computer monitor and subsequent digital processing of grating images. Maximum fringe order is only about one owing to use of coarse grating. Sensitivity was enhanced using phase shifting. From Asundi, A., "Novel Techniques in Reflection Moiré," *Experimental Mechanics* 34(3):230–242 (1994). Photo courtesy of Dr. Anand Asundi, Professor, Division of Engineering Mechanics, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

Reflection moiré is deserving of study because of its:
- *unique features and applications in structural analysis,*
- *significance in understanding and extending other optical methods,*
- *ease of implementation.*

Reflection moiré:
- *involves recording the image of a remote grating that is reflected in the polished surface of a specimen,*
- *requires, in its simplest form, exposures for the "before" and "after" states of the specimen,*
- *yields directly a moiré pattern that is a map of the slope change between the specimen states,*
- *is especially applicable to plates and similar engineering structures,*
- *can be applied over a large range of sizes,*
- *requires very little equipment and is simple to implement.*

The Series, Optical methods—Back to Basics, *is written by Prof. Gary Cloud of Michigan State University in East Lansing, MI. It 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.

If you have comments or questions about this series, please contact Jen Proulx, journals@sem1.com.

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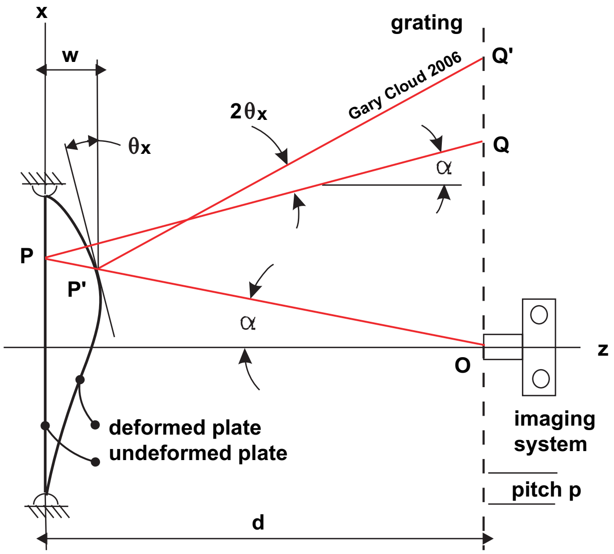

resulting small errors are eliminated in other ways. The master grating has a hole at its center, and a camera is set up behind the hole, aimed at the plate, and focused on the virtual image of the grating as it is reflected in the polished plate. If the camera aperture is small enough so that the depth of focus is large, then the plate itself will also be imaged by the camera lens and appear to have the grating image superimposed on it.

A first exposure is taken with the specimen in its initial state, which here is taken for convenience to be the flat unloaded position as shown in the sketch. The grating element at point Q is reflected to the camera from point P on the plate, and this grating element appears at the image of point P on the photograph. Angle α describes both the viewing angle and the reflection angle for point P in this case of the initially flat plate. The plate is then deformed so that it becomes a curved mirror. Point P on the plate has moved to point P′, which, to a reasonable approximation for small deflections, is imaged to the same location on the film as point P. Because of the slope change at P′, grating element Q′ is now superimposed on this same image point in the second exposure. The effect in the image is that the reflected grating has shifted, thereby producing a moiré pattern in the double-exposure image.

Rather than analyze the grating shift and the resulting moiré pattern at the camera image plane, it is instructive and convenient to calculate the grating shift from Q to Q′ as it appears at the specimen. If θ_x is the change of slope $(\partial w / \partial x)$ at point P as it moves to P′, then the law of reflection indicates that the line PQ in the sketch rotates through angle $2\theta_x$ as it moves to position P′Q′. The apparent relative shift δ of the grating between exposures is found to be approximately:

$$\delta = d[\tan(\alpha + 2\theta_x) - \tan\alpha] \qquad 23.1$$

If p is the pitch of the grating, then the relations used before in our study of moiré fringes indicate that there will be produced at the point in question a moiré fringe of order N, where $N = \delta / p$. For the case shown in the sketch, the grating will have shifted in the reflected image of point P by three grating lines, so the fringe order at P will be three.

The distance d from camera to specimen is ordinarily large compared with plate dimensions. Assume also that the slope of the plate is nowhere very large. In that case, the usual paraxial approximation pertains, and the equation relating slope and fringe order is found by combining results given above, with the result:

The basic experimental setup requires:
- *a specimen such as a plate with a reflective surface fixed in a loading frame,*
- *an illuminated flat or curved coarse master grating fixed at some distance from the plate,*
- *an imaging device set up behind a hole in the grating to record the reflected grating.*

Procedure:
- *photograph the reflected grating for the initial state of the specimen,*
- *load the specimen,*
- *photograph the reflected grating for the final state of the specimen,*
- *superimpose the photographs or use double exposure.*

As the slope at a point on the plate specimen changes, different portions of the master grating are reflected from that point. The reflected grating seems to distort and sweep across the image of the specimen as it deforms.

$$\theta_x = \frac{Np}{2d} \qquad 23.2$$

If the viewing distance is large relative to plate size, then the slope of the plate at any point is the moiré fringe order times the grating pitch divided by twice the viewing distance.

Attach no importance to the assumption that the initial state of the plate was flat. If it is not flat, then the change in slope from initial state to final state is obtained.

Notice that effects of the out-of-plane or in-plane deflections from P to P' on the apparent relative shift of the grating in the double-exposure photograph are ignored in this analysis. Also, the initial slope and the change of slope are assumed "small." While such approximations are appropriate for typical beams or plates subjected to relatively small bending displacements ($w << d$), they may lead to errors for membranes or shells where the displacements or the slopes are large. In that case, more sophisticated analysis is required. The situation is somewhat analogous to that discovered for projection moiré (see Part 22 of this series) in that one is comparing the initial slope of one point with the final slope of a different point if the point P' deviates much from the line OP as the specimen deforms.

PRACTICAL ISSUES

The error caused by use of the simplified Eq. 23.2 can be ascertained for a given arrangement by the use of the more exact Eq. 23.1 for various points off axis in the field of view. Practically, one makes d large and uses a lens of long focal length in the camera to enforce paraxiality. Otherwise, a good bit of the error in the paraxial approximation can be eliminated using a grating that is curved to a cylindrical shape. The gratings are just ruled on posterboard, and they are easily mounted on curved rails sawn from plywood. Ligtenberg showed that the optimum radius of curvature of the master grating is about $3.5d$. If the slopes are large, then the more exact equation must be used even if the setup is paraxial.

For complete analysis of the plate or other object, except where symmetry pertains, the slope in the y-direction θ_y must also be measured. Independent observation of θ_y requires that either the specimen or the grating be rotated 90° about the optical z-axis of the system and that a second double-exposure photograph be made.

Good sensitivity can be obtained with rather coarse gratings, and the grating can be simply ruled on posterboard or created with a computer printer.

A striking feature of this method is that it provides excellent sensitivity with coarse gratings and with no phase shifting. The grating pitch required for a given arrangement and a specified sensitivity is easily determined from the equations given above. For example, if d is 2 m, and if one fringe is to represent 10^{-3} radian, then the pitch is 4 mm. Such a reference grating can be fabricated by ruling the lines with a pen onto a sheet of posterboard or by using computer graphics and a printer.

ENHANCEMENTS

The fringe contrast in all types of double-exposure moiré photos tends to be marginal. Nonlinear high-contrast processing is helpful. Fringe visibility can be greatly enhanced using optical spatial filtering as described in Part 15 of this series.

The fact that the gratings used are relatively coarse implies that digital imaging and computer processing of the images to create the moiré patterns can be used to great advantage. In fact, why print a grating at all? Researchers have used grating images as displayed on a monitor screen as the master grating, an approach that provides excellent control over grating pitch and orientation. Phase shifting by lateral displacement of the master grating can then easily be accomplished with resulting improvement of sensitivity.

Of course, the reflection technique can be applied to vibrating objects through the use of strobe lighting and/or averaging techniques. The potential for studying whole-field vibrations of components such as auto body parts by this simple method seems endless.

Improvements include:
- *use of a curved grating,*
- *rotating the specimen or the grating to obtain slopes in both directions,*
- *using a grating image on a computer monitor as the master,*
- *use of digital imaging and computer superposition of the grating photos,*
- *implementing an alternative setup that gives the slope map with only one exposure,*
- *using strobe lighting or averaging techniques to study dynamic problems.*

An improved but more complex optical system for reflection moiré that yields a slope change pattern with a single exposure in real time was described by V. Parks in 1987. It is thought provoking that the setup is reminiscent of that used for Michelson interferometry even though optical interference is not involved. A. Asundi, among others, has invented many improvements to both the hardware and the data processing for static and dynamic cases.

WHAT IS NEXT?

It is likely that the next article in this series will begin a discussion of laser speckle phenomena, as was promised earlier. ■