OPTICAL METHODS Back to Basics *by Gary Cloud*

Optical Methods in Experimental Mechanics

Part 18: Geometric Moiré Phenomena and Simulations

REVIEW AND PURPOSE

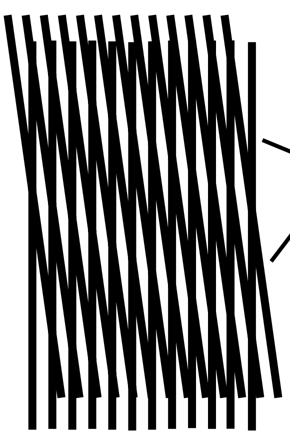
The optical phenomena studied so far in this series have involved interference and diffraction of light waves. A useful optical effect that does not involve the wave nature of light now deserves attention.

Experience suggests that moiré phenomena are most easily grasped if they are demonstrated visually and conceptually ahead of presentation of theory. This article describes basic moiré effects and shows in detail how simple computer-based simulations can be employed to teach them quickly.

GEOMETRICAL MOIRÉ

The geometric moiré or mechanical moiré effect is the mechanical occlusion of light by superimposed patterns to produce another pattern that is called a moiré fringe pattern. It is not an optical interference effect. Geometrical moiré is the basis for a family of methods for measuring deformation, strain, shape, and contour. Advanced moiré methods, including moiré interferometry, are easily understood if the principles of geometric moiré are known. Even speckle "interferometry" can be seen as a moiré process.

The figure below illustrates the basic moiré phenomenon that appears when one system of closely spaced straight lines, a grill or grid, is lain over a similar set.



The two sets have different line spacings, and one set is also rotated slightly with respect to the other. At certain locations, the lines from one set block the gaps in the other set so that no light is allowed through. If the line spacings are sufficiently small, then the areas where the light is blocked appear to join up to form another system of broad lines, called a moiré fringe pattern. Simple experimentation shows that moiré fringes possess properties that are very useful in measuring small relative motions.

MOIRÉ IN THE WILD

Moiré effects are ubiquitous but are usually not noticed because our visual processing system is conditioned to ignore distractions. The photograph below shows a moiré pattern that was captured in the wild.

Other examples that create visible moiré fringes include:

- referees' shirts, performers' neckties, or pictures of buildings on television, where the moiré fringes are caused by interactions of the pattern in the scene with the pixel array in the video picture,
- bridge supports or lattice fences when viewed from a distance,
- layers of curtain material or insect screen when backlit,
- certain items of lingerie.

TEACHING MOIRÉ

Typically, geometric moiré is illustrated in the classroom using transparencies that contain grills, gratings, and other patterns. Models of low-modulus elastomers that carry a printed grating are useful for showing semi-quantitatively how moiré can be used to measure deformations, but these models are difficult to make for many non-specialists. While laudable, these approaches are somewhat expensive in terms of instructional time, and it is difficult to make clear

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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 noted otherwise, 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 any comments or questions about this series, please contact Kristin Zimmerman, Kristin.b.Zimmerman@gm.com.

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the relationships between fringe spacing, fringe orientation, relative rotation between the gratings, and grating deformation.

An approach that is effective in cost, time, and comprehension is to use vector graphics software to generate the gratings and superimpose them in the classroom. The gratings can be manipulated in real time to illustrate all important moiré effects. Students are able to reproduce and extend the demonstrations as homework. Examples using CorelDraw® (version 8) are described in detail below.

SIMULATION OF BASIC MOIRÉ PHENOMENA

First, important facts relevant to the creation of moiré patterns and their uses in measurement are established through the following steps:

1. Click the *View* drop-down menu and select *Enhanced*.
2. Use *Format* then *Page Layout* to select landscape orientation of the page. This step is convenient but not necessary. Alternatively, eliminate the page border unless you want to print the moiré examples that will be created.
3. Click *Tools,* then *Options,* then *Edit* to access the box that allows you to set the horizontal duplicate placement (offset) to .2 in. and the vertical duplicate placement to zero. On this same menu, set the *Nudge* to .05 in., which is 1/4 of the duplicate placement. This nudge spacing facilitates demonstration of a typical procedure for phase stepping. These values are somewhat arbitrary, but they are good starting points and they reduce aliasing problems with the monitor raster.
4. Use the freehand *Line* tool to draw a vertical line that extends about 3/4 of the page height. It is best to arrange this line so it does not show any “jaggies.”
5. Use the *Pen* tools to set the line width to .1 in, which is 1/2 of the duplicate spacing selected above. Be sure the line you just drew is selected, then *Apply*.
6. Select *Edit* and then *Duplicate* (otherwise *Control-D*) and repeat the duplication to create an array of lines that is approximately as wide as it is tall. The result is a bar and space grating with the bars and spaces of equal widths.
7. Use the cursor to create a box around the entire array of lines or else use *Select-all objects*.
8. Click *Group* from the *Arrange* drop-down menu or else just click it on the toolbar if it is showing.
9. Make sure that the array is selected, then do *Edit* and *Duplicate* again. At this point you have two line arrays superimposed, with one offset from the other.
10. In order to identify the two separate arrays, you can move one slightly upwards and/or use the *Outline Pen* tool or *Pen Dialog* tool to change the color of each of the two arrays. Complementary colors work well.
11. At this point, you are ready to demonstrate basic moiré effects.
12. Click one of the arrays twice, then use the cursor-directed rotation feature to illustrate the effect of rotating one of the gratings relative to the other. Clear moiré fringes should be produced.
13. Observe the following:
    - Rotation fringes are perpendicular to the grating lines and can be used to measure relative rotation.
    - Small relative rotations produce large movements of the moiré fringes, even with these rather coarse gratings. The moiré effect seems to serve as a motion magnifier.
    - Zoom to a larger magnification to observe that dark fringes are created where the lines from one grating block the spaces in the other grating. Light fringes happen where the lines from the two gratings coincide.
    - Zoom out to low magnification. Observe that the fringes begin to visually predominate over the grating lines. The reason is that the monitor-visual system is acting as a low-pass filter.
14. Select *Edit* then *Undo Rotate* to get back to two parallel arrays. If you become lost after several rotations or other manipulations, simply do *Edit* and *Cut* the rotated grating. Then re-duplicate the original grating.
15. Select one of the gratings by clicking on it. Use the *Stretch* feature to demonstrate the effect of uniformly elongating one of the gratings in the direction perpendicular to the lines. This case corresponds to a uniform strain field. While at it, compress or stretch one of the gratings in the direction parallel to the lines. The moiré pattern will be unchanged.
16. Observe the following:
    - These fringes are oriented parallel to the grating lines, meaning that stretch effects are decoupled from rotation effects.
    - The fringe spacing decreases (more fringes) with increased stretching.
    - Many fringes are created with relatively little stretching, even with these coarse gratings, again making the point that the moiré effect is a motion magnifier.
    - Evidently the fringe spacing could be used to determine strain, a fact that can be proven.
    - Zoom in and out to illustrate the ideas established above about the formation of the fringes and the low-pass filter.
    - Moiré can be viewed as an example of the “beat phenomenon.”
17. Combine some of the above steps to create moiré fringes from a combination of stretch and rotation.

That moiré fringes serve as motion magnifiers is very important in the context of experimental mechanics where we face the problem of measuring strain, which is the small change in a large quantity. Assuming success with the demonstrations outlined above, proceed to demonstrate the creation of moiré fringe patterns for nonuniform displacement fields in elastic bodies.

MOIRÉ SIMULATION FOR A BEAM IN PURE BENDING

Simulate a classic in-plane moiré experiment by supposing the following:

- One of the gratings is somehow printed onto the central portion of a beam that is in pure bending, as with four-

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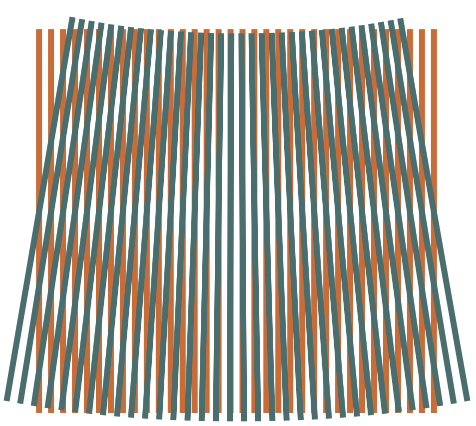
point loading. This grating will be distorted as the beam is bent.
- The undistorted grating is used as a reference, meaning that it is superimposed with the distorted specimen grating so that the one is viewed through the other.

Undertake the following steps with the drawing software:

1. Start with the two gratings created as instructed above. It is best to hoist one slightly above the other, but make the lines exactly coincide.
2. Select *Effects* then *Envelope* to obtain the envelope pull-down menu. This function will be used to deform one of the gratings.
3. Select one of the grouped grating arrays by clicking on one of its lines.
4. In the envelope menu, select *Add New,* which will place a set of adjustable nodes connected by dotted lines around the grating.
5. Deselect *Keep lines*.
6. Select the *single arc* box in the *Envelope* menu. This box contains a figure with a concave top.
7. Locate the cursor over the center-top node of the envelope. Left-click and drag the node down about 1/4 inch. You will see that the upper boundary of the grating bends to the arc of a circle, or close to it.
8. Note: If you need to reshape the envelope after completion of one of these simulations, select the object and use the *Node adjust* tool.
9. Repeat step 6 for the center-bottom node.
10. The preceding steps have rearranged the grating into the arc of a circle, which is consistent with pure bending of a beam. The trouble is that no moiré fringes are produced. The reason is that we have not yet satisfied the condition that beam cross sections rotate while remaining flat.
11. Select the *straight line* box in the *Envelope* menu. This one is identified by a trapezoid.
12. Locate the cursor over the bottom-left node of the envelope. Left-click and pull this node about 3 line spacings to the left. You will see some moiré fringes appear.
13. Move the top-left node about 3 line spacings to the right.
14. Similarly, move the top-right node to the left and the bottom-right node to the right.
15. The result is the well known moiré fringe pattern for a beam in pure bending, where the fringes are loci of constant longitudinal displacement. An example of the result is shown in the reproduction below.



16. Observe that the simulated deformation is large and the number of fringes is small. The reason is that the gratings used are coarse. Repeat this demonstration with finer gratings to fix the idea that finer gratings give greater sensitivity.
17. Use the *line drawing* tool to place a horizontal line on the fringe pattern. Recall that the moiré fringes are loci of equal horizontal displacement. So, if fringe order is plotted as a function of distance along this line, this function may be differentiated to determine strain.

SIMULATION OF PHASE STEPPING

At this stage, the concept of phase-stepping or compensation that is used in all forms of interferometry may be demonstrated. Notice that the fringes created so far are quite far apart, and a much higher density of data is needed for accurate strain determination. Phase stepping affords a means to obtain these data. It is demonstrated as follows, starting with the beam deformation simulation just created:

1. Be sure one of the gratings is selected, then place the cursor over, say, a light area somewhere between two dark fringes. What is the exact fringe order at this location?
2. Use the *Nudge* function (e.g. the right arrow key) to move the selected gratings sideways by the amount set at the beginning of these instructions. The fringes on either side of the cursor location will move with successive nudges.
3. Notice that 4 nudges gets us back to the original moiré pattern. If 3 nudges moves a dark fringe to the cursor, then the fractional fringe order at the chosen point is $\pm 3/4$.
4. That this process can be performed over the whole field simultaneously using digital imaging to measure intensities and a computer to do the necessary calculations should be apparent, although the details demand further attention.

MOIRÉ SIMULATION FOR INDENTOR PROBLEM

Simulation of another classic elasticity problem is quite easy to perform using the envelope functions that were used for the beam example. That the fringe pattern produced is exactly correct is doubtful, but the results are striking and useful for instruction.

1. Start with two gratings atop one another, as before. Select one of the gratings.
2. From the *Envelope* pull-down, select *Add Preset*.
3. Select the *second square from the left* from the preset choices. This step creates a square with several nodes within the grating chosen.
4. Place the cursor over the right-center node, left click and drag that node to the left about 1/2 inch.
5. The result seems to be a moiré pattern where the fringes are loci of constant displacement in the direction of the load axis. An example appears below, only here the master grating has been nudged to the right to illustrate the effect of phase stepping, and the entire pattern has been rotated 90 deg.

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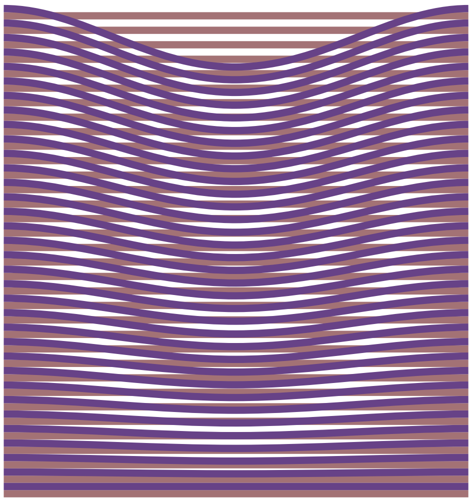

COMMENTS

One problem that appears in these demonstrations is that, at certain line spacings and magnifications, moiré interactions between the grating image and the monitor scan raster will be visible and might even predominate. Experimentation will reduce these distractions for a given computer setup.

Many variations on the themes outlined above can be conceived and executed. Also, other geometric patterns can be easily generated or extracted from the textures libraries furnished with graphics software, and these can be used for interesting demonstrations. However, simple line gratings serve to illustrate most of the phenomena and relationships that are useful in experimental measurement applications of moiré. Be warned that, while instructive, exploring moiré phenomena on a computer can be somewhat addictive.

WHAT IS NEXT

The next article will deal quantitatively with in-plane geometric moiré and establish the relations between fringe order, rotation, and strain. ■

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