Optical Methods in Experimental Mechanics
Part 22: Projection Moiré

REVIEW AND PURPOSE

Shadow moiré, which is a very simple technique for generating a contour map of an object, was described in the Part 21 of this series.

Projection moiré is another simple method for obtaining contour maps, for measuring changes of contour resulting from deformation, or for comparing the shapes of two objects. At first glance, it seems very similar to the shadow method; but it is actually quite different in function, it provides unique data, and it demonstrates particular advantages for certain applications.

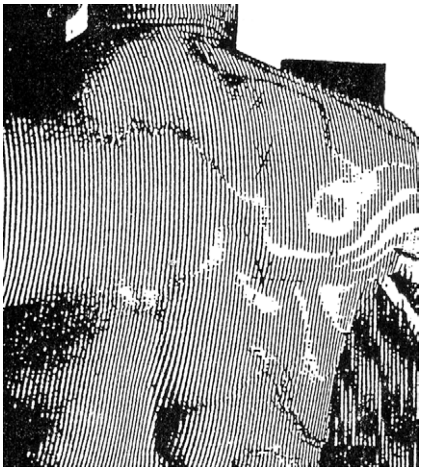
WHAT IS PROJECTION MOIRÉ?

Projection moiré in its most basic form is accomplished by creating an image of a reference grating on the surface of a specimen by use of a slide projector or by using oblique interference of coherent light (see Part 4 of this series). The grating is projected obliquely to the viewing direction. This projected grating is photographed, meaning that the imaging system must be capable of resolving the grating lines. The specimen is then moved, deformed, or even replaced with another specimen while the grating projection and imaging systems remain unchanged. The grating, as projected onto the changed specimen, is also photographed, usually as a second exposure over the first one. When the double-exposure picture is developed, a moiré fringe pattern will be seen. The fringe orders are loci of constant *difference of elevation* along the viewing direction between the two specimen states for each point in the picture.

The difference between the shadow and projection approaches is important. Shadow moiré, recall, yields the difference of elevation between the master grating and the specimen. If the master is flat, as is usual, then an absolute contour map is obtained. Projection moiré, on the other hand, provides the difference of elevation between two projected grating images. In other words, it yields directly the changes in the contour map that occur during an experiment. If one is interested in, say, the change of shape that result from loading a specimen, then projection moiré is the method of choice. To obtain change of shape (as opposed to absolute shape) with shadow moiré, the initial contour map must be subtracted from the second one. The problem is poorly conditioned because of the usual difficulty of determining accurately the small changes in a large quantity.

ANALYSIS OF PROJECTION MOIRÉ

The sketch below shows in cross section a simplified optical setup for analysis of the horizontal component of displacement by projection moiré. The grating pitch and specimen displacements are exaggerated for visualization, and the distance from specimen to camera is foreshortened.



Projection moiré fringe pattern showing change in topography of human back with muscular effort required for 20% adduction of the upper arm. Photo by P.J. Moga and G.L. Cloud, 1991

Projection moiré is a simple technique that provides:
- *contour maps of objects,*
- *changes of contour caused by deformation,*
- *comparisons of contours of two different objects.*

The steps in basic projection moiré are:
- *project a grating on a specimen as by a slide projector,*
- *photograph this grating,*
- *deform the specimen or replace it with a different object,*
- *photograph the grating a second time, often by double exposure,*
- *develop the doubly exposed film to see the fringes resulting from superimposition of the two distorted gratings,*
- *interpret the fringes to obtain the map of change of elevation between the two specimen states.*

Projection moiré yields the change in contour of a specimen, whereas shadow moiré gives an absolute contour map.

The series, 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, Michigan. 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.

If you have comments or questions about this series, please contact Kristin Zimmerman, kristin.b.zimmerman@gm.com.

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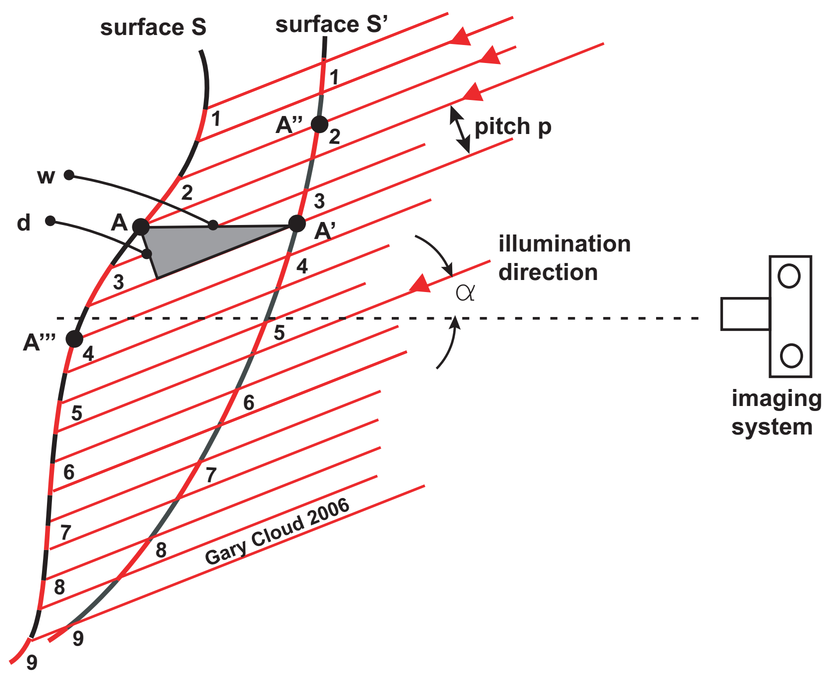

Surface S is the specimen in its initial state. A grating of pitch p, represented by the alternating red and black line segments, is projected obliquely onto the surface by a device that keeps the pitch constant in space. This condition is approximated by using a slide projector that is placed far from the specimen (paraxial approximation); it can be attained exactly by using interference of coherent plane waves to create the grating (oblique interference). Photography of the grating image is parallel to the horizontal optic axis, which implies that a field lens is used. Otherwise, this condition is approximately attained by placing the imaging system far from the specimen.

The grating as projected onto the specimen surface is recorded by the imaging system. The specimen is then deformed and/or moved to its second state, represented in the sketch as surface S', and a second image of the projected grating is recorded. Assume for now that the before and after images are recorded on the same piece of photographic film. When developed, the film contains two superimposed grating images, and a moiré fringe pattern is created.

Interpretation of the fringe pattern requires analysis of the relation between horizontal movement of the specimen and the fringe order. For the moment, consider the simplified case where a typical point such as A on surface S moves axially to location A'. The effect of lateral shift of the specimen will be considered presently. Examination of the shaded triangle in the sketch shows that as A undergoes axial movement w to A', it cuts across the projected grating by the amount $d = w\sin\alpha$. In this particular location, point A has moved from the bottom end of grating line 2 on S to the bottom end of grating line 3 on S'. Recall what has been taught in this series about fringe formation in geometric moiré, e.g., one moiré fringe is created when m grating lines are expanded to fill the space of m+1 grating lines. So, at location AA' in the doubly-exposed photograph, the fringe order will be one. In general, for any point in the field, the fringe order $N = d/p$. Combining the relationships given above and inverting the result gives the axial displacement w in terms of fringe order N as,

$$w = \frac{Np}{\sin\alpha} \qquad 22.1$$

For the basic setup and assuming paraxial conditions are met, the change of elevation along the direction of viewing is the fringe order times the pitch of the grating divided by the sine of the angle between the projection axis and the viewing axis.

This result is fundamental in the interpretation of projection moiré fringe patterns, no matter how the gratings are created or how they are recorded.

EFFECT OF LATERAL MOTION

Consider now the effect of lateral motion of the specimen point A. Suppose that the point moves to location A" in the sketch. The key fact is that, in the double-exposure image, the laterally shifted point A" is no longer superimposed onto the image of the original point A. Rather, its place will be taken by some other point on surface S, such as point A'", that will have moved to location A' after the specimen deformation. The moiré fringe order created at specimen point A shows the elevation difference between original point A and the new position of A'" because it has moved to point A'.

Specimen motion perpendicular to the imaging axis does not affect the meaning of the fringe pattern. But the fringe pattern no longer compares the "before" and "after" elevations of the same specimen point.

This point is subtle and not widely appreciated, but it is very important. In general, fringes in projection moiré are not necessarily associated with the "before" and "after" states of the same point. This characteristic of the projection technique can be a blessing or a curse, depending on the application.

One distinct advantage of this peculiarity of projection moiré is that the difference in contours between two distinct objects can be measured directly. The first exposure is recorded using the first object, then the second object is put into its place for the second exposure.

Because the projection technique involves two different pictures of a projected grating, two entirely different specimens can be compared to obtain the difference between them.

The fringe pattern gives the contour difference. If either object is flat, then the fringes indicate absolute contour of the other object. Otherwise, the mismatch between the two objects is determined. One application of this idea is in quality control of stamped or molded objects. A master prototype can be used for one exposure, and faults in production samples obtained through this comparison process.

SOME PRACTICAL CONCERNS

An advantage of projection moiré over the shadow method for some applications is that a large master grating is not required. Only a good quality high-density grating of a size that fits an ordinary slide projector is needed.

Projection moiré gratings are created by:
- *using a Ronchi ruling in a slide projector,*
- *using oblique interference of plane coherent light,*
- *creating a master using computer graphics and using a presentation projector.*

This requirement is met by obtaining a Ronchi ruling from a laboratory supply house. Otherwise, the projected grating can be created by oblique interference of two laser beams, as suggested above. A very practical approach is to create a grating master using computer graphics and project it onto the specimen using a digital presentation projector.

A disadvantage of the projection moiré technique is that the imaging system must be able to resolve the grating as projected onto the specimen; and, to satisfy the paraxial assumption, the imaging must be done from a distance.

Unlike shadow moiré, the projection technique requires that the imaging system be able to resolve the projected grating lines. This restriction limits the sensitivity of the technique and requires that quality optics be used.

If the imaging optics are marginal for the fineness of grating used, then the contrast of the grating images will be low or zero, and the fringes will not be readily visible. If photo films are being used, then nonlinear film processing and optical spatial filtering can be used to improve data quality.

In practice, adherence to the paraxial conditions is difficult. If a slide projector is used to create the specimen grating, then the grating will be diverging in space even if the projector is quite far from the object. For large specimens, a field lens is likely too costly for consideration, so the imaging camera is at some finite distance from the object. Under these conditions, Equation 22.1 is accurate only on the optic axis.

The basic fringe order-elevation change equation is in error if paraxial conditions are not met. The grating projector and the imaging device should be far from the specimen to reduce these errors.

To properly interpret fringes for off-axis points or to assess the error resulting from use of Equation 22.1 for these points, the fringe-displacement relationship must be worked out for finite projector and camera distances. This problem has been analyzed in detail, but the solution is not presented here.

ENHANCEMENTS

Recording of the projected gratings is often best done nowadays using a digital camera. Moiré fringes are then obtained by subtraction of one image from the other in a computer. Problems with this approach are evident. One is that the resolution of ordinary digital cameras is not high enough to resolve fine grating structures, so, depending on the camera, only rather coarse projected gratings can be used. The second problem is that moiré interactions between the grating image and the sensor array (aliasing) can compromise the fringe data in unexpected ways.

Digital photography of the grating and digital processing of the grating images:
- *can create resolution and aliasing problems,*
- *facilitates rapid processing of the data,*
- *allows significant refinements such as phase stepping and filtering to improve accuracy and sensitivity.*

The advent of digital image acquisition and processing has greatly improved the capability of projection moiré. For example, phase stepping can be used to increase sensitivity, digital data reduction speeds processing, and digital filtering improves signal-to-noise.

Projection moiré can be accomplished through the use of a scanning laser beam to create the grating on the specimen line-by-line. Some of the laser scanning methods for obtaining digitized surface shape profiles in industry are, basically, the same as projection moiré, although the data are processed differently.

Certain laser scanning methods for obtaining digitized surface shape profiles in industry are essentially the same as projection moiré.

SAMPLE APPLICATIONS

Whereas shadow moiré was shown to be useful for mapping the contour of biomechanical structures such as the human body, projection moiré is useful for determining the changes of contours with loads or stresses. One application is to measure the change of contour of trunk or limbs with muscular effort for diagnosis of muscle or nerve problems. The lead photograph with this article is a simple example from such an experiment. The use of the projection technique in quality control of manufactured objects has already been mentioned. The method is also used in the aircraft industry to check the contours of fuselages and wings under load, and to determine the sizes of dents that result from bird strikes and the like.

Applications include:
- *measuring changes of contours of human or animal body components caused by muscular effort,*
- *comparing shapes of manufactured objects with a prototype for quality control,*
- *observing contour changes in aircraft structures.*

WHAT NEXT

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