# Optical Methods in Experimental Mechanics

## Part 33: Photoelasticity V—Fringe Patterns

### REVIEW AND PURPOSE

The previous article on photoelasticity observables demonstrated how measured light intensity is related to stress magnitude and direction for the case where a single light wave passes along one transect of the photoelastic model. In the first case, light is extinguished when the principal stress axes at the point in the model are aligned with the crossed axes of polarizer and analyzer. This result yields principal directions at that point. In the second case, no light reaches the sensor when the relative retardation is an integer multiple of the wavelength. This result gives the difference between the principal stresses at the point if the stress-optic coefficient of the model material is known. This pointwise approach is very useful, but it is also seriously limiting in that it does not exploit the broad-field capability that is a significant advantage of optical methods.

This article extends our analysis to the whole field so as to obtain fringe patterns that are easily observed, recorded, and interpreted to concurrently obtain stress magnitudes and principal stress directions over the entire extent of the photoelastic model. The approach is rather self-evident, given that we have used the relevant concepts previously in this series. The ensuing discussion is necessary but hopefully not tedious; some subtle traps can be avoided if care is taken to get formulations correct from the beginning.

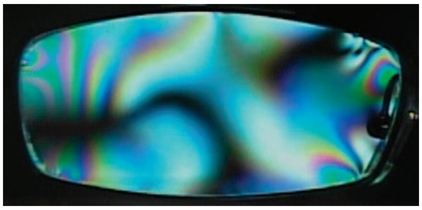
### WHOLE-FIELD INTERFEROMETRY

In order to obtain and interpret whole-field fringe patterns, apply the concept that was outlined in part 3 of this series, further developed in part 4, then utilized in explaining various other types of interferometry as in part 5 on Newton's fringes. The idea is to interrogate all points in the model at once by using a bundle or beam of light waves to create a multitude of interferometers, each of which acts according to the rules developed in the previous two articles. To accomplish this purpose, a collimating lens is added to the polariscope setup discussed in part 31 to collect light waves from the source and create a collimated beam. Then, in order to view or photograph the entire model with the imaging device, a field lens must also be added. Recall that similar steps were used to obtain whole-field Newton's fringes (part 5) and in Michelson interferometry (part 8). Under certain circumstances, useful fringe patterns can be obtained with the lenses omitted, and such alternative polariscope systems will be discussed in a subsequent article.

### THE WHOLE-FIELD LINEAR TRANSMISSION POLARISCOPE

The sketch below shows in cross section the classic linear transmission polariscope.

As is usual with schematics of this sort, only the central and extreme rays in the light beam are shown. The light source approximates a point source as closely as is practicable. Important is that the distance from the source to the collimating lens must equal the focal length of that lens in order to create a columnar beam of



**Photoelasticity pattern in a plastic corrective spectacle lens obtained with white light and a linear polariscope. The several orders of colored isochromatic fringes indicate significant stress levels and high stress gradients. The black isoclinic has two segments that cut across the isochromatics. Photo courtesy of Dr. Gaetano Restivo of Michigan State University, 2008.**

*Photoelastic analysis is extended to the whole field so as to obtain fringe patterns that are easily observed, recorded, and interpreted to concurrently obtain stress magnitudes and principal stress directions over the entire extent of the model.*

*All points in the model are interrogated at once by using a collimated beam of light to create a multitude of interferometers acting in parallel.*

*To create the beam of light, a point light source is used with a collimating lens. To view the entire model, a field lens is also added to the polariscope, as is an imaging device.*

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*The series,* Optical Methods—Back to Basics*, is written by University Distinguished Professor 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.*

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

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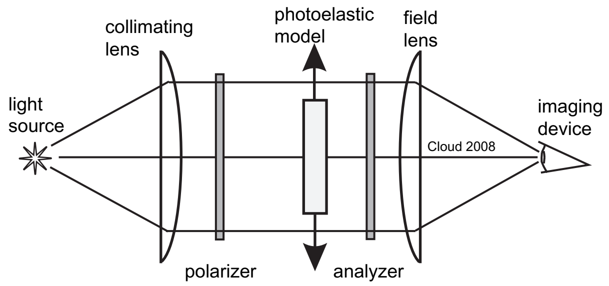


parallel waves. If this rule is not followed, then errors are induced because most of the light waves do not strike the model normal to its surface. Likewise, the distance from the viewing point to the field lens must equal the focal length of the field lens in order to obtain a picture of the whole model. The most convex faces of the two lenses should face one another to reduce aberrations, and the lenses should match one another for the same reason. Finally, the field lens and analyzer should be close to the model to reduce distortion in the recorded image. Some liberties may be taken with these setup guidelines, but only with foreknowledge of the effects on quality of results.

## WHOLE-FIELD FRINGE PATTERNS

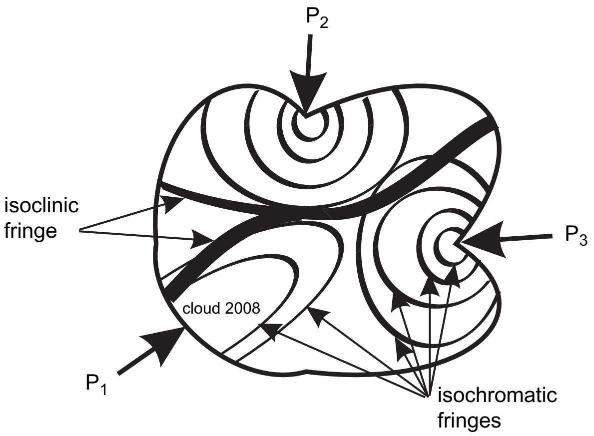
Assume for a moment that the light source is monochromatic. Now, if the relative retardations (path length differences) and/or principal directions varied randomly over the extent of the model, then the whole-field interference pattern would be a random pattern of light, gray, and dark points. If, however, the relative retardations and/or stress direction variations are created by a spatially-continuous process such as is true of deformation of a solid, then all those spots that have common retardations and/or principal directions join up to create patches of uniform intensity in the image. Such patches, as we have learned, are called interference fringes. In photoelasticity, the interference fringes are loci of points having constant relative retardation or constant inclination of principal axes, but we see them as loci of points of equal intensity. A typical interference fringe picture, such as the one shown at the top of this article, contains several such loci, and it is called a fringe pattern.

*The relative retardations and/or stress direction variations are spatially continuous in a deformed solid, so all the spots that have common retardations and/or principal directions join up to create patches of uniform intensity, called interference fringes, in the image.*

A confusing factor, as is implied by the "and/or" options mentioned above, is that two separate fringe systems appear in any photoelastic pattern obtained with the linear polariscope. Those of the first type are called *isoclinic fringes*, while those of the second type are called *isochromatic fringes*. The illustration below suggests how these fringe systems might look in an image of an imaginary loaded photoelastic model that is examined in a linear polariscope using monochromatic

*Two different fringe systems appear in a photoelastic pattern taken with a linear polariscope, namely:*

- *isoclinic fringes,*
- *isochromatic fringes.*



illumination. A photoelasticity pattern of this type that was obtained in the laboratory appears in part 32 of these articles. Let us examine and define the two types of fringes separately.

## ISOCLINIC FRINGES

Recall from the previous article that no light passes through the system if the principal stress axes are aligned with the crossed axes of polarizer and analyzer. When extended to the broad field, a dark patch or fringe will extend over any and all points of the model image where the principal axes are parallel to the polarizer and analyzer axes. The name given this type, isoclinic fringes, means “fringes of constant inclinations.” When properly recorded and interpreted, isoclinic fringes provide a map of principal stress directions over the extent of the model.

An isoclinic fringe can be defined in at least three ways that are equivalent, namely:

1. It is a locus of points in the photoelastic model having constant inclinations of the principal axes of refractive index.
2. It is a locus of points in the photoelastic model having constant inclinations of the axes of principal stress.
3. It is the locus of points in the photoelastic model where the principal stress axes are aligned with the axes of polarizer and analyzer.

Having more than one definition for a measurable physical quantity can be confusing. Usage is largely a matter of preference, but it also depends on scientific discipline (e.g., physics, solid mechanics, materials science).

*An isoclinic fringe can be defined in at least three equivalent ways as a locus of points:*

- *that have constant inclinations of the principal axes of refractive index,*
- *that have constant inclinations of the axes of principal stress,*
- *where the principal stress axes are aligned with the axes of polarizer and analyzer.*

Note that for any one angular setting of crossed polarizer and analyzer relative to the model, only one isoclinic will be seen, although it might be branched or broken into segments. Also, the isoclinic fringe will be black, it is usually quite broad, and it does not move as the load on the photoelastic model is changed. If the load is held constant and the crossed polarizer and analyzer are rotated relative to the model, then the isochromatic fringes are stationary and the isoclinic appears to move, although it is actually being replaced by a new one. The isoclinic dominates wherever it crosses isochromatics, meaning it is a nuisance when one is trying to decipher the isochromatic fringe pattern.

*Isoclinic fringes:*

- *provide a map of principal stress directions over the extent of the model when properly collected and interpreted,*
- *are black, even with white-light illumination,*
- *appear as only one fringe, perhaps broken into segments, for given azimuth settings of polarizer and analyzer,*
- *remain stationary as the load on the model is changed,*
- *appear to move when the crossed polarizer and analyzer are rotated relative to the model,*
- *dominate wherever they cross isochromatic fringes.*

## ISOCHROMATIC FRINGES

The previous article demonstrated that no light passes through the polariscope if the relative retardation at the point being interrogated is an integer multiple of the wavelength of the illumination. When the broad model field is examined, dark points that are a specific multiple of the wavelength connect up to create a dark patch that is called an isochromatic (constant color) fringe. That is, an isochromatic fringe will connect points where the relative retardation is one wavelength, and this one is called a first-order fringe. Another isochromatic, called a second-order fringe, connects points having relative retardation equal to two wavelengths, and so on.

Recall that the relative retardation can be written in terms of principal stress difference or maximum shear stress, and we are guided to five equivalent ways of defining isochromatic fringes:

1. They are loci of points of constant color.
2. They are loci of points of constant path length difference.
3. They are loci of points of constant relative retardation.
4. They are loci of points having constant principal stress difference.
5. They are loci of points having constant maximum shear stress.

Since the relative retardation depends upon stress and therefore upon load on the model, several isochromatic fringes typically appear in a photoelastic pattern. Unlike isoclinics, these fringes move as the load is changed, becoming more numerous and closely packed as the load is increased.

*Isochromatic fringes can be defined in at least five equivalent ways as loci of points having:*

- *specific uniform color,*
- *constant path length difference,*
- *constant relative retardation,*
- *constant principal stress difference,*
- *constant maximum shear stress.*

In order to obtain stress from isochromatic data using Eq. 32.7 (see part 32), the fringe orders must be correctly assigned. As has been mentioned before, this task is not trivial. One complication is that, for example, a second-order fringe looks much the same as a fifth-order fringe, and the pattern might not even contain a zero order. Often, there will be more than one patch in a model where the relative retardation has a particular value, meaning that, say, a seventh-order fringe might exist in two or more locations. These behaviors complicate fringe counting. We are helped by the realization that, for spatially-continuous processes, adjacent fringes will differ by no more than one order. There are several tricks of the trade that help with fringe order assignment, and mention of them is planned for a subsequent article.

*Isochromatic fringes:*

- *yield stress amplitude data if the model stress-optic coefficient is known,*
- *change with changes in load,*
- *become more numerous as load is increased,*
- *must be correctly numbered to obtain quantitative data.*

## COLORED ISOCHROMATIC FRINGES

We assumed that monochromatic light is used and we referred only to light and dark patches. Why, then, are the fringes that depend on stress magnitude called lines of constant color? The likely reason is that when Scottish physicist Sir David Brewster discovered the stress-birefringence effect in 1815–1816, he used white light in his experiments, as did his successors. If nonmonochromatic light is used, then the isochromatic fringes are indeed loci of points of constant color. The photo at the head of this article shows a multitude of colored isochromatic fringes, as have several other photoelastic patterns that have been used in this series, including that appearing in part 1.

*If white light is used, the isochromatics are colored. If monochromatic light is used, the integer-order isochromatics are black.*

The formation and interpretation of colored interferometry fringes is a somewhat complex subject that was discussed extensively in part 7 of this series, so it is not pursued again here except in one aspect. When photoelasticity is carried out with white light, the zero-order isochromatic fringe, which is the locus of points where the relative retardation is zero, appears black. In some cases, this fringe does not even move as the model load is changed. Distinguishing this black zero-order isochromatic fringe from the black isoclinic can be vexing.

## A CAVEAT

The requirement for collimated light seems to imply that the light column should be of constant cross section throughout its length. This conclusion is valid only if the light is radiated from a true point source, something not attainable in practice. Otherwise, the light beam should diverge by a small angle that depends on the size of the source.

## WHAT IS NEXT?

The next articles of this series will deal with some alternative polariscope configurations and the use of circularly polarized light to separate the isoclinic from the isochromatic pattern. ■

*The next articles in this series will consider:*

- *alternative polariscope configurations,*
- *circularly polarized light,*
- *separation of the isoclinic from the isochromatic pattern.*