# Optical Methods in Experimental Mechanics

## Part 44: NEXUS

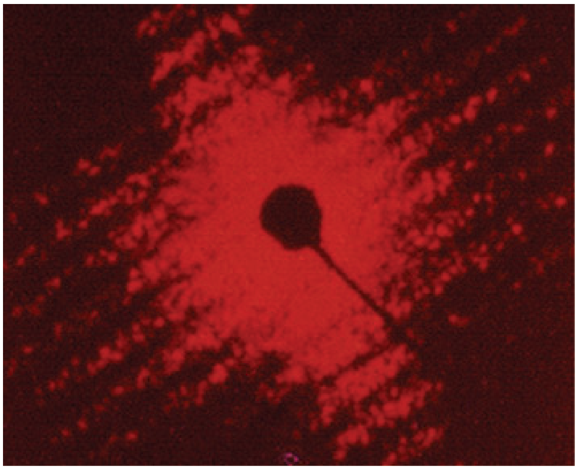
### PREAMBLE

- Nexus: noun—. . .a means of connection, tie, link; a connected series; a core or center. . .
- This article is a review, summary, and outline. It seems not amenable to the provision of marginal notes that summarize important points, as has been the practice for all the other articles in this series.
- Owing to space limitations, the inventors and developers of the techniques included here are not given due credit except for the cases of our scientific ancestors.

### REVIEW AND PURPOSE

The previous article of this series concluded a basic handbook on photoelasticity with an exposition about three-dimensional photoelasticity. It brought us to a nexus in the treatment of optical methods with the bold statement that, if you are current with these articles, then you are in position to understand and practice almost any type of optical measurement.

This article supports that contention by reviewing briefly the fundamental pillars or unifying concepts of optical methods plus related subsidiary concepts, by reminding us of our debts to the earliest inventors of optical techniques, and by pointing out the ways in which these pillars are incorporated into several of the modern measurement techniques that are available to experimental mechanicians. Details of execution are not mentioned. The bonus result is an outline of future topics for this series.



**Young's fringes showing displacement magnitude and direction at a point in turbulent flow of fluid obtained by laser interrogation of a double exposure white-light speckle photograph recorded using closely sequenced strobed lighting. The flashlamp timing is measured, so the velocity vector can be calculated. The fluid was seeded with fine aluminum powder. The black spot at the center of the pattern is the is the shadow of the mask that occludes the intense central beam. Digital scan of 35 mm slide recorded by G. Cloud, J. Peiffer, and R. Radke at Michigan State University in 1979.**

### THE TWO PILLARS

- **Interference:** The first critical concept in optical measurement is that optical path length differences can be measured by interference of two light waves that are coherent. Usually, the interference is between beams or wave bundles so as to produce whole-field fringe patterns that change as the path length differences within the field change. Counting fringes allows one to determine either absolute path length difference or changes of the difference. An important special case of interference is that of oblique incidence, wherein two collimated plane-wave groups cross each other so as to produce a fringe pattern that is a system of parallel lines. The line spacing depends on the wavelength and the crossing angle.
- **Diffraction:** The second fundamental pillar is diffraction by an aperture. Here, light is passed through a hole, which might contain some intelligence such as a transparency or a grating. Under certain conditions, the distribution of illumination falling on a screen downstream from the aperture is proportional to the Fourier transform of the information contained in the aperture. That is, the illumination at a point on the observing screen indicates the relative strength of a corresponding spatial frequency component in the aperture signal. Diffraction is thus seen to be a frequency analyzer. To gain control of the transform process, a lens is usually placed behind the aperture, in which case the transform is located in the focal plane of the lens. The original intelligence in the aperture can be reconstructed by performing an optical inverse transform with another

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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, Michigan. 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, Professor 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 Tingets, journals@sem1.com.*

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lens. An important special application is when the frequency content of the original signal is modified in the transform plane by a so-called spatial filter, a process often called Fourier optical processing.

## ADDITIONAL USEFUL CONCEPTS

- **Interferometer types:** Recall the critical differences between common-path interferometers and non-common-path setups. The interfering waves in the first case follow the same path through the optical system, as is true of photoelasticity and Newton's rings. Common-path instruments are not seriously affected by vibrations and other disturbances, so they are easiest to set up and they adapt well to field use. Non-common-path devices, e.g. the Michelson interferometer and its progeny, tend to be sensitive to noise and are trickier to implement, but they can yield information that cannot be obtained with the other type.
- **Geometric moiré:** When a pattern such as a grating is superimposed over a similar structure, a third structure that looks like an interference fringe pattern is produced. This third pattern indicates the differences in position, orientation, and pattern properties, such as line spacing, between the two superimposed structures. This effect is created by simple occlusion of light and is not caused by interference, so it is usually called geometric moiré. It is used to map rotations and displacements in large areas of a specimen at various levels of sensitivity. Techniques used to perform the superposition of the grating patterns include projection, reflection, shadow, and direct grating photography with subsequent optical processing.
- **Phase difference measurement:** Precise measurement of path length difference requires accurate determination of phase difference between the interfering waves. So far in this series, only fringe counting has been suggested. Other approaches, including fractional fringe measurement, intensity measurement, and phase shifting have been alluded to, but more learning on these topics is required.
- **Laser speckle:** As one observes or photographs an object that is illuminated with coherent light, as from a laser, the image will exhibit a granular appearance that is called laser speckle. It is caused by interference between the waves that are scattered by the specimen surface. Speckle causes objectionable noise when recording pictures, but it is very useful in measuring displacements.
- **Use of nonvisible wavelengths:** Interference between waves can occur at all wavelengths of the electromagnetic spectrum. The interferometric methods discussed in this series of articles may be performed at, for example, microwave, radio, infrared, and ultraviolet wavelengths. This fact allows measurements such as by photoelasticity on materials that to us seem opaque.

## CLASSICAL INTERFEROMETRIES

The two unifying concepts in optical measurement have been illustrated and applied in discussions of several important theories, experiments, inventions, discoveries, and measurement techniques including Young's fringes, Newton's rings, Lloyd's mirror, Doppler interferometry, Michelson interferometry, and Fourier optical processing. Nothing more needs to be said of these fundamental experiments except to reiterate their historical, scientific, and practical values. Many so-called "modern techniques" are identical to or derived from these early works. Were it not for the profound thinkers and experimenters whose names are attached to their discoveries, the universes of physicists and engineers would be different, likely much more primitive, than they are now.

## PHOTOELASTICITY

Likewise, little more needs to be said of photoelasticity except to underline some key characteristics and reasons for studying it intensely. These points are categorized as follows.

- Photoelasticity is a useful peadagogical paradigm for teaching how the concept of interference can be combined with knowledge of light sources, lenses, imaging equipment, and materials to perform measurements. This learning is extended to gain understanding of other optical methods lying inside and outside the domain of experimental mechanics.
- Photoelasticity is an important measurement tool for engineers. It is a common-path interferometer that is very simple to implement. It is the **single technique of experimental mechanics that is capable of providing direct measurement of stress**. Further, it yields the stress or strain values over the entire extent of the specimen or structure. All other techniques yield only strain at a point, which is sufficient for many problems; or, worse, they map only displacements, which must be differentiated to obtain strain. Differentiation of experimental data is always problematical, and the results must be viewed with the eye of a critic.

## MOIRÉ INTERFEROMETRY

Moiré interferometry is a highly sensitive method of mapping displacements over a large area. It utilizes oblique interference of two beams and diffraction by a grating, thus involving both of the fundamental pillars mentioned above. Oblique interference is used to create a fine grating of parallel lines. This grating profile is transfered to the specimen surface by one of several techniques. The specimen with its grating is then placed back into the oblique interference setup and loaded, which causes the specimen grating frequency to be changed a little bit. Both of the incident beams are diffracted by the specimen grating, but the diffraction angles are changed because the specimen grating is deformed. The two diffracted beams cross at a shallow angle or are made to do so by a lens. The result of this oblique interference is a fringe pattern that turns out to be the same as the geometric moiré pattern that would have been created had the original grating and the deformed grating been directly superimposed.

## HOLOGRAPHY

Holography is the only way to store and create a true three-dimensional image by preserving all the phase data in the waves that are scattered from an object that is illuminated with coherent light. It is a two-step process that utilizes both interference and diffraction. To record the data, the light from the object is mixed with a reference beam to create an interference pattern that is recorded on photographic media. This pattern is a very complex diffraction grating. To reconstruct the object wave, the hologram grating is illuminated by the reference beam. The diffracted beam carries all the data about size, shape, and depth that were contained in the original object beam. When the eye is placed within one of the diffracted beams so as to look through the hologram, it will see an exact replica of the original object. Many special variations of holography have been invented.

## HOLOGRAM INTERFEROMETRY

The image generated via the holographic process is so exact that it may be interferometrically compared with another such image. One way to do this is to create two holograms in the same photo emulsion. The first hologram is made as outlined above, but the photo emulsion is not developed. Instead, the specimen is deformed and a second hologram is recorded in the same film, after which the film is developed. The holographic images are then reconstructed. The result is two images that are superimposed. The phase differences between the two reconstructed object beams cause them to interfere and produce in the image a fringe pattern that is indicative of the surface displacements of the specimen. In the simplest case, the fringes are analogous to Newton's rings and indicate out-of-plane displacement.

## INTERFEROMETRIC STRAIN GAGE

This technique utilizes oblique interference and diffraction to measure strains in tiny gage lengths at high temperatures, in delicate specimens, and with a high dynamic capability. In its simplest form, small indentations or grooves are made in the specimen by a diamond point. The indentations are illuminated by a laser. The light is either diffracted by the indentations in a manner reminiscent of Young's experiment with two pinholes or else, if the indents are relatively large and far apart, it is simply scattered by the them. Oblique interference occurs in the far field to create a fringe pattern. Changes in the fringe pattern indicate changes in the gage length, from which the strain can be calculated.

## LASER SPECKLE INTERFEROMETRY

The formation of laser speckle in an image through interference has been mentioned above. In laser speckle interferometry, also called Electronic Speckle Pattern Inteferometry or Digital Speckle Pattern Interferometry, the intensity of each speckle in the field is measured as an indicator of the phase relationships between the waves that interfered to produce that speckle. Relatively large speckles are used so that, as the specimen is deformed, a given speckle will still overlap its original boundary. The specimen deformation does, however, cause the intensity of each speckle to change because of the changes of phase of the waves forming the speckle. The new intensity of each speckle is captured and subtracted from the original intensity. The change of intensity is related to the specimen deformation at the location of the speckle. For maximum utility, this intensity capture and calculation of intensity change must be performed simultaneously for each of the thousands of speckles in the specimen image, meaning digital capture and electronic processing are a good idea. Different optical arrangements are used for measuring in-plane and out-of-plane displacements. In the out-of-plane case, the fringes have the same meaning as Newton's rings; and this arrangement is often used for optical nondestructive inspection. For the in-plane setup, appropriate processing of the phase data and the use of phase shifting yield dependable measurements of strain. Notice that, unlike holography, the speckle images do not interfere and only intensity maps are used. One is led to think that this and other speckle methods are closely allied to geometric moiré except that the superimposed structures are random rather than regular.

## LASER SPECKLE SHEAROGRAPHY

In this family of techniques, two separate speckle images are created simultaneously by a device such as a Dove prism or a split lens and caused to overlap with one image slightly displaced from the other. The intensity of each resultant speckle in the overlapped images is recorded. The specimen is deformed and the new intensity pattern recorded. The intensity maps are subtracted to give data related to the specimen deformation. As with speckle interferometry, different setups are used to obtain specific information. In the most common out-of-plane detection mode, the fringe orders are related to the in-plane derivative of the out-of-plane displacement (i.e. slope). Unlike speckle interferometry, shearography is, in its out-of-plane measurement form, a common path interferometer. It is tolerant of noise and vibrations, and hand-held speckle shearography devices are commercially available and successfully used in the field for nondestructive inspection. A thought-provoking feature of shearography is that oblique incidence interference fringes are created within each of the combined speckles. Superposition of the before- and after-deformation patterns would create moiré fringes, so, again, the relationships between speckle methods, geometric moiré, and moiré interferometry become apparent.

## LASER SPECKLE PHOTOGRAPHY

This simple technique for determining displacements over a broad field relies on interference and diffraction. Interference causes the laser speckle, as suggested above. The optical system is adjusted to create very small speckles. As usually practiced, the speckled image is recorded on a photograhic film, which is not yet processed. The specimen is deformed so as to cause the speckles in the image to move, and the new speckle pattern is recorded on the same film via double exposure. The developed film carries thousands of speckle pairs, with the separation between each pair being the local displacement. There are two good ways of measuring pair separations. The first and easiest is to generate Young's interference fringes (diffraction by a pair of apertures) by passing laser light through the film. The fringe spacing and orientation yield the relative spacing and orientation of the pairs in the illuminated area, so the local displacement vector is determined. The second method utilizes diffraction and Fourier optical processing to obtain a full-field image containing interference fringes that are loci of constant displacement vector. Notice that in speckle photography the speckles are used only as a fine system of surface markers.

## WHITE LIGHT SPECKLE PHOTOGRAPHY

Study of laser speckle photography, wherein the speckles are used merely as surface tags, gives rise to the following questions, "Why is it necessary to create the speckles using a laser?" and, "Could not the fine pattern of surface markers be created by paint spatters or even by oblique non-coherent illumination of a "rough" surface?" The answer to both questions is, "yes." Here, one simply creates a very fine speckle in the image of a surface by one of the methods mentioned. The pattern is then photographed for two states of the specimen to obtain a double-exposure speckle photograph similar to that described above. Extraction of the data from the white-light speckle photograph parallels that outlined for laser speckle photography using diffraction to obtain Young's fringes or through optical spatial filtering. The resulting fringe patterns are usually noisier than those obtained via laser speckle photography, and the dynamic range is not as wide. Elimination of the laser from the optical setup greatly expands the potential of the technique. It has been used at high temperatures, in dynamic studies of fluid flow and deformation of human skin *in vivo*, and in the field on buildings, salt mines, and glaciers. Two recording cameras are usually used in a stereoscopic arrangement in order to obtain displacements in three dimensions.

## DIGITAL IMAGE CORRELATION

This powerful technique is proving to have applications too numerous to mention. In some ways, it may be viewed as a highly developed extension of white-light speckle photography, but it has eclipsed the latter method in laboratories. The creation of the speckle pattern and the data collection are similar to those used in speckle photography except that the pattern images are captured electronically and stored in a computer. Again, more than one camera is usually used to provide three-dimensional capability. The data processing is entirely different. Briefly, a mathematical cross-correlation function between the before-deformation and after-deformation speckle patterns in subsets of the each speckle array is calculated as a function of position and local displacement gradients. Minimization of this function yields a map of the displacement.

Neither interference nor diffraction are involved in digital image correlation, and one might ask why it is included in this paper. One reason is to emphasize once more the relationship between speckle methods and geometric moiré. The former can be thought of as "random moiré." Alternatively, geometric moiré might be considered to be a special case of speckle photography or digital image correlation where the speckles are replaced by an ordered grating. Indeed, displacements can be obtained from geometric moiré grating photographs using Young's fringes, whole-field Fourier processing, or, presumably, a correlation function.

## X-RAY DIFFRACTION

Diffraction of an x-ray beam from the crystal lattice in material is the basis of this technique. Strain in the specimen causes the lattice spacing in crystalline material to change. This change causes the diffraction angles to be shifted. Sensors measure the change in the diffraction pattern, from which an estimate of the strain in the interrogated area is derived.

## WHAT IS NEXT?

The next article will take on a subject that has been mentioned many times in these articles, specifically the precise determination of phase difference in interferometry beyond fringe counting and estimation of fractional fringe order. We will learn about compensation, phase shifting, and phase unwrapping. ■