Optical Methods in Experimental Mechanics

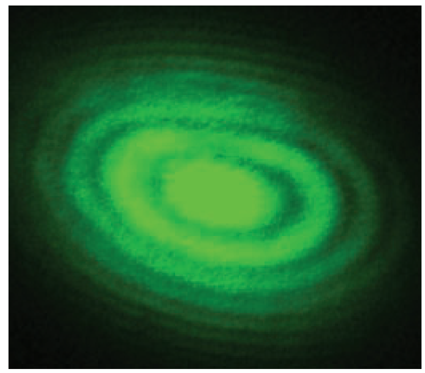
Part 47: Measuring Phase Difference—Part III: A Phase-Shifting Setup

REVIEW AND PURPOSE

Established in the previous article was the concept of precisely measuring interferometric fringe order by compensation, which requires placing into one of the optical paths a device that changes the path length by a known amount. This procedure facilitates the use, if desired, of a photometric instrument to measure intensity.

We now extend the compensation idea by automating it so as to quickly obtain path length difference (phase difference) maps over the entire optical field. This family of techniques is called phase-measurement interferometry, phase-stepping interferometry, or phase-shifting interferometry. The choice of name depends to some extent on details of implementation, but we happily ignore these distinctions for the time being.

In undertaking phase-shifting interferometry, we must decide what measurements are needed, how to collect them, and what to do with them. This analysis is expedited if we first familiarize ourselves with the basic apparatus. That step is undertaken in this article.



Interference pattern produced with a Michelson Interferometer using a green laser. Image by Falcorian. Reproduced under the Creative Commons Attribution Share-Alike License v. 2.5.

This article describes a basic phase-shifting interferometer and discusses its limitations and possible refinements.

A BASIC SETUP FOR PHASE SHIFTING

The figure at the top of the next page shows a minimal arrangement whose purpose is the interferometric measurement of the shape and/or change of shape (e.g. displacement d_p) of a nearly flat reflective specimen such as a plate or diaphragm. You might recognize it as a practical realization of the generic interferometer (see Part 3 of this series) or as a variation of the Michelson interferometer (see Part 8). While it is not an optimum configuration, this pattern is deliberately chosen as a tutorial model because: (1) it is inexpensive and easy to set up; (2) it is a useful pedagogical exemplar; (3) it can be made to give good results; and (4) it allows us to point out some important limitations and refinements as well as the reasons for them. For clarity in the sketch, the path lengths are shorter relative to the beam widths than they properly would be in the laboratory. Also, the principal rays of the beams are coded for tracking purposes.

The Michelson-type reflection interferometer is chosen as a tutorial model because it:

- *is inexpensive and easy to set up,*
- *is a useful pedagogical exemplar,*
- *can be made to give good results,*
- *allows us to point out some important limitations and refinements.*

Before getting into details, note that this basic arrangement and others like it have an extraordinary range of applications. If the sensor array is replaced by a photo emulsion, the setup can be used without modification to make a hologram, view a hologram, and perform holographic interferometry. As it stands, it can be used for speckle interferometry with or without phase shifting, Doppler

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The series, Optical Methods—Back to Basics, *is written by University Distinguished Professor Gary Cloud (SEM Fellow) of Michigan State University in East Lansing, Michigan. It began by introducing the nature and description of light and is progressing through topics ranging from diffraction through phase shifting interferometries. The intent is to educate through narrative discussion and marginal summaries coupled with illustrative photos and diagrams that can be used by practitioners in the classroom as well as in industry. Professor Cloud is internationally known for his work in optical measurements and for his book,* Optical Methods of Engineering Analysis. *Unless otherwise noted, the graphics in this series were created by the author.*

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

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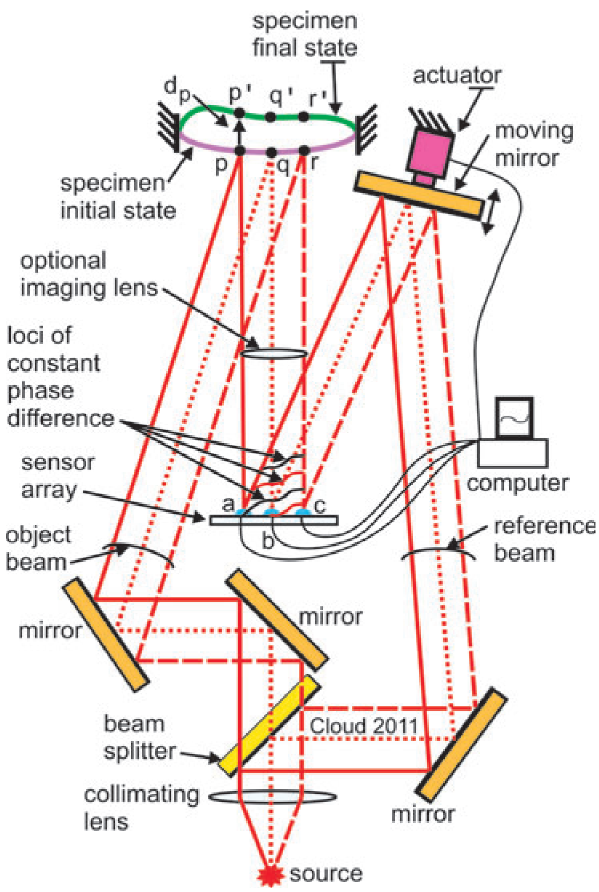

velocimetry, and so on. In each case, minor improvements can be incorporated to improve performance, but the basic layout remains the same.

FUNCTION OF THE INTERFEROMETER

It has been awhile since we have discussed interferometers, so let us expend some energy in reminding ourselves how this device functions and outlining its limitations and possible improvements. Light of sufficient coherency, probably from a laser, is collimated by a lens, after which it is divided into two collimated beams by a beam splitter that is likely a partial mirror. One beam, called the object beam, is directed so as to illuminate the specimen, which, as mentioned, is close to being flat and also is highly reflective. The angles of the mirrors are adjusted so that the reflected object beam falls onto an array of photocells, which could be the sensor array in an electronic video or still camera with its lens removed. The specimen and the sensor plane should lie normal to the axis between them. The second beam, called the reference beam, is routed to fall onto a mirror that is attached to some sort of actuator, perhaps a piezoelectric crystal, so that the mirror can be translated along its normal. This element is the phase shifter and creates, when properly calibrated, known path length differences in the reference beam. The orientation of this mirror is adjusted so that the reference beam impinges on the sensor array. The positions of the mirrors are adjusted during the setting-up so that the object beam path length, from the beam splitter around to the specimen and on to the sensor, is approximately equal to the reference path length. A hank of string is useful in equalizing these path lengths. A lens whose purpose is to cast an image of the specimen onto the sensors is included in the sketch as an option that is discussed later in this article. This interferometer is of the amplitude division, non-common-path type, so measures to eliminate the effects of vibrations must be implemented.

The function of the interferometer is as follows:

- *Coherent light is collimated.*
- *The light is then divided into two beams by a beam splitter.*
- *The object beam illuminates the specimen, which is flat and reflective.*
- *Light from the specimen is reflected to an array of sensors.*
- *The reference beam is diverted to the phase shifter, which is a mirror that can be translated by an actuator.*
- *The reference beam is then directed to the sensor array.*

The phase-shifting mirror could be placed at any of the other mirror locations in the setup, including in the object beam. Be aware that the induced path length changes depend on the incidence and reflection angles at the mirror, a factor that must be taken into account as the phase shifter is calibrated.

As we have learned, surfaces of constant intensity (interference fringes), which are loci of constant phase difference between the object and reference beams, are generated in the space where the beams overlap. The sensor array transects this system of fringes, and each of its elements generates a voltage that is proportional to the local irradiance falling on that element. Given enough sensors, a map of the intensity distribution across the optical field is obtained.

Because numerous sensors are required to adequately map the intensity distribution, a computer with data acquisition and management capability is useful. Its main purpose is to create and store the voltages from each sensor (pixel) along with the sensor location. As a further step in automation and data management, it is helpful if the phase shifting actuator is controlled by the computer. The idea is to efficiently record an intensity map, induce a phase shift, record a second intensity map, and so on until enough phase-shifting data are recorded. An algorithm reduces the data to phase-difference maps and finally to initial and final specimen shapes, or, more commonly, the difference between them. Because of the way our brains work, it is nice if the computer converts the results to a picture.

- *Surfaces of constant intensity caused by interference between the reference and object beams are created where the beams overlap.*
    - *These surfaces are loci of constant phase difference.*
- *Each sensor in the array generates a voltage that is proportional to the local irradiance.*
- *A computer records each sensor voltage and the location of the sensor, the result being a map of intensity distribution in the plane of the sensor array.*
- *The computer signals the actuator to move the phase-shifting mirror so as to introduce a known change of path length difference.*
- *The sensor voltages are again recorded.*
- *This process is repeated until enough data are recorded.*
- *An algorithm reduces the data to a map of phase difference.*
- *The phase difference map(s) are reduced to displays of initial and final specimen shape, or the difference between them.*

LIMITATIONS OF THE BASIC SETUP

While this basic arrangement has the advantage of simplicity and low cost, it suffers limitations that actually are a result of its simplicity. These issues include the following:

1. If the specimen is not reasonably flat in both its initial and final states, some of the rays falling on it will not be reflected onto the sensor array but will deviate away into space. The specimen deformation must, therefore, be small. Recall, however, that the purpose of interferometry is to measure motions to within a fraction of a wavelength of the light used and over a range of typically not more than 50 wavelengths, so this limitation might not be serious.
2. Because only reflection is utilized, as is typical of Michelson-type interferometers, and assuming no imaging lens is included, establishing correspondence between a particular sensing element and a point on the specimen can be difficult. This factor might severely limit applications involving quantitative measurement of shape or displacement profiles.
3. If the specimen scatters light, then each sensor element receives light from all points on the specimen. The phase difference measured at a sensor cannot be correlated with a particular specimen point.
4. The phase difference result depends partly on the angle between the object and reference beams. If they are not collinear (oblique interference), a sensitivity vector calculation shows that the out-of-plane displacement measurement is contaminated by in-plane displacements.
5. The sharp observer will notice that the fore-aft motion of the phase shifter causes the reference beam to move laterally at the sensors and will wonder how this shift affects results. Recall from the previous article that the induced path length changes are fractions of the wavelength, so the effects of the beam shift might be negligible.
6. Because the beams are expanded to their final diameters near the source, the beam splitter and the mirrors must be large. This problem is most serious at the phase shifter, because the actuator must be powerful enough to quickly start and stop mirror motion. The mirror will tend to flex and vibrate and so introduce errors into the phase difference map, cause noisy signals, and/or slow the data acquisition.

Limitations of the basic setup include:

- *The specimen must be reasonably flat in both its initial and final states.*
- *If no imaging lens is included, establishing correspondence between a sensing element and a point on the specimen is difficult.*
- *The specimen must not scatter light.*
- *The reference beam is not collinear with the object beam.*
    - *Oblique interference causes in-plane movement to contaminate the measurement of out-of-plane displacement.*
- *Motion of the phase-shifting mirror causes discrete but usually small lateral shifts of the reference beam.*
- *The mirrors must be large.*
    - *The heavy phase-shifting mirror is actuated only with difficulty.*

REFINEMENTS

The difficulties enumerated above may be eliminated by introducing some relatively simple modifications into the apparatus. These additions bring with them certain burdens, including added cost and complexity. Listed here are the most obvious refinements along with brief summaries of their disadvantages.

1. Limitations 1 through 3 are easily solved by the addition of a lens between the specimen and the sensor array, an option shown in the illustration. The lens is adjusted to create an image of the specimen on the array. In other words, put the lens back into the camera. No matter the specimen shape or its deformation, within reason, the lens establishes a direct correspondence between a sensor element and a specimen point. If the specimen surface scatters light, then the imaging is made more uniform and efficient. In fact, the specimen should not be reflective if a lens is used, because such a surface tends to create hot spots in the image that will saturate the sensors. The positive gains from introducing an imaging lens usually outweigh the negative aspects, which are two. The first is that the lens receives a cone of light from the object, and the incidence angle of the object (image) beam onto the sensors varies over the field. These facts imply that limitation 4 is exacerbated. The induced error varies from zero on the optical axis to a maximum at the extremes of the field, but the error can be minimized by control of the geometry. The second problem is that some other means of getting the reference beam onto the sensor array might be required. One way of doing this is to add a partial mirror between the lens and the sensors or even in front of the lens. As mentioned next, this measure offers another benefit.
2. A convenient way to minimize the effects of oblique interference (limitation 4) is to arrange the apparatus so that the path lengths are long relative to beam diameters. The better solution is to add a partial mirror between the specimen and sensors to steer the reference beam so that it is collinear with the object beam. This method is the same as that used in the classic Michelson setup, and its implementation is suggested in the first figure of the previous article. The price is some loss of light.
3. Limitations 5 and 6 are solved by expanding and collimating the object beam on its approach to the specimen. Likewise, the reference beam is not expanded and collimated until it is on its final approach to the sensor array. The result is that only a very small beam splitter and small-diameter mirrors are needed. The phase shifter can be small and light, therefore easily moved. The beam expansions are implemented with microscope objectives, often in tandem with pinhole spatial filters (see Part 14). Collimation is accomplished with simple lenses. If some measurement accuracy can be sacrificed, then the collimating lenses may be omitted.

The limitations of the basic setup can be eliminated by introducing the following refinements:

- *A lens may be used to create an image of the object on the sensor array.*
    - *Correspondence between points on the specimen and the sensor elements is established.*
    - *The specimen need not be flat.*
    - *The specimen need not be reflective but should have a matte finish to scatter the light.*
    - *Errors caused by ray obliquity might be introduced, but these can be minimized.*
- *The path lengths should be made long relative to beam diameter to reduce the effects of oblique interference on the measurement.*
- *The reference beam can be steered so it is collinear with the object beam by introducing a partial mirror between the specimen and the sensor array.*
- *The reference beam may be expanded and collimated on its approach to the sensors, and the object beam may be expanded and collimated as it approaches the specimen.*
    - *The beam splitter and mirrors can be small.*
    - *The phase-shifting mirror can be small, light, and easily actuated.*

WHAT IS NEXT

The next articles will utilize the setup described above to show what intensity data must be acquired and to explain the simplest algorithms for converting the data to phase change maps and subsequently to a picture of the specimen shape or deflection. ■

The next articles will:

- *show what data must be acquired.*
- *explain the simplest algorithms for converting the intensity data to phase change maps and to a picture of the specimen deflection.*