

# OPTICAL METHODS Back to Basics *by Gary Cloud*

## Optical Methods in Experimental Mechanics Part 3: Path Length and the Generic Interferometer

### INTRODUCTION

In Part 2, we learned how a phase difference between two waves can be converted to an intensity variation through the phenomenon of interference, thereby making measurement of the phase difference possible. Now, we focus attention on what might cause the phase lag and, in general terms, the essential components of an interferometric arrangement for measuring it.

To get at the phase difference, we must know how to describe the length of the path that a wave travels. The optical path length depends on both the physical length of the path and the wave speed, which is most easily quantified by the refractive index.

### INDEX OF REFRACTION

The wave equations studied in Part 1 showed that the speed of travel of a wave depends on material properties. For practical purposes, we normalize the speed of light in a material to the speed of light in a vacuum ( $c \approx 3 * 10^8$  km/sec) by defining an absolute index of refraction as:

$$\text{Absolute index of refraction} = n_1 = \frac{\text{Speed of light in vacuum}}{\text{Speed of light in material 1}}$$

Sometimes, it is convenient to define a relative index of refraction between two materials as:

$$\text{Relative index of refraction} = n_{12} = \frac{\text{Speed of light in material 2}}{\text{Speed of light in material 1}}$$

This relative index might be used to describe the speed of light for material 1 when it is immersed in material 2. In this case, two subscripts are used, with the first referring to the object and the second to the immersion medium. Be careful to get these relationships right-side-up; it is natural to invert them. Many writers do not carefully distinguish between relative and absolute indexes, particularly when describing experiments where the immersion medium is air. To reduce confusion, this series of articles will use only the absolute index. Note also that as far as we know, the speed of light is maximum in a vacuum; so the index of refraction for materials is greater than 1.

### OPTICAL PATH LENGTH

The length of the path traveled by a light wave, for measurement purposes, depends on the physical length of the path and the speed at which the wave travels over the path. Conceptually, it is the time it takes for the light to cover the path. However, since we usually normalize the speed relative to vacuum, the path length has units of distance.

$$\text{Optical path length} = [\text{physical distance traveled}] \text{ times } [\text{index of refraction}]$$

**Editor's Note:** Optical Methods: Back to Basics, is organized by ET Technical Editor, Kristin Zimmerman, General Motors, and written by Prof. Gary Cloud (SEM Fellow) 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 in 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.

The series author, Prof. Gary Cloud (SEM Fellow), is internationally known for his work in optical measurement methods and for his recently published 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.



*Micro-photoelasticity interferogram showing stress state near a single glass fiber embedded in epoxy matrix after fiber rupture. Courtesy of Dr. Pedro Herrera-Franco† and Dr. L.T. Drzal‡*

*Phase difference is a function of optical path length, which depends on:*

- *physical distance*
- *the speed of travel of the wave*

*Wave speed in a medium is described by its refractive index, which is the ratio of speed in the medium to the speed of light in vacuum.*

*Optical path length is the product of the physical path length and the index of refraction.*

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## OPTICAL METHODS IN EXPERIMENTAL MECHANICS

### PATH LENGTH DIFFERENCE

In experimental mechanics measurement, we are interested in the change in a path length or else the difference between two path lengths; this is called a path length difference (PLD). The PLD is what causes the phase lag.

We can determine PLD directly by using the definition given above, but let us instead conduct a thought experiment. Imagine a race between two waves, as depicted in Figure 1.

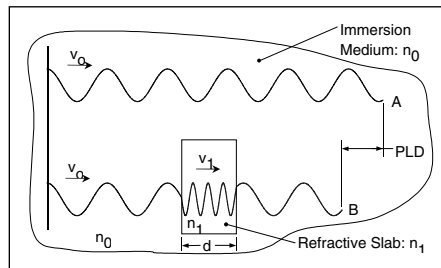


Fig. 1 Determination of PLD

The entire event is immersed in a medium that has a refractive index  $n_0$ . The first wave leaves the starting line, and arrives at point A at time  $t_1$ . The second wave leaves the start line at the same instant the first wave left. But, this wave is required to pass through a slab of refractive material having index of refraction  $n_1$  and thickness  $d$ . At time  $t_1$ , this second wave will have attained only point B, because it was slowed down for a spell while traversing the slab. The distance by which the second wave lags behind the first is the PLD for this problem. It is also called the “absolute retardation”  $R_1$ .

The calculation of the PLD is straightforward since it involves only velocity-time-distance considerations. It is the difference between  $d$  and the distance that the first wave travels in the time required for the second wave to traverse the refractive slab. The result is:

$$\text{PLD} = \left[ \frac{n_1 - n_0}{n_0} \right] d$$

A nice aspect of this approach is that it automatically corrects for the immersion medium, a factor that might not be intuitively obvious by the more direct calculation. Clearly, a change in either of the refractive indexes or a change in the distance  $d$  will create a PLD. This notion brings some unity to the various optical methods of experimental mechanics. Finally, it is easy to extend this result to the case where each of the waves meets a separate slab of refractive material.

### A GENERIC INTERFEROMETER

All but one of the methods of optical measurement in experimental mechanics are based on the process of measuring PLD by interference. The exception is “geometric moire.”

A unifying conceptual model of the process of interferometry (measurement of PLD using interference) is depicted in Figure 2.

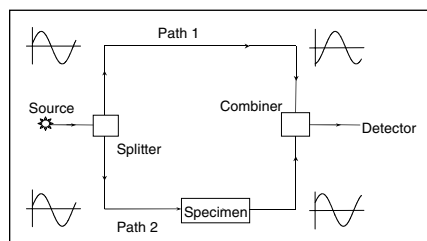


Fig. 2 Generic interferometer

*Path length difference (PLD) between two waves is:*

- the main quantity of interest in interferometric measurement
- the difference between two optical path lengths

*PLD depends on:*

- refractive index of the surrounding medium
- refractive indexes of materials in either or both of the optical paths
- physical distance that each wave travels

*Most optical methods of measurement in experimental mechanics involve the measurement of PLD using interference.*

*The “generic interferometer” is a unifying conceptual model of the process of interferometric measurement that converts PLD to intensity.*

## OPTICAL METHODS IN EXPERIMENTAL MECHANICS

This model shows all the necessary elements that are common to interferometry measurements, meaning that the devices shown appear in one form or another in all interferometry setups. Since the waves in the two paths must be able to interfere, they must come from a common source. A divider or beam splitter separates the two waves, and the waves travel along different paths, one or both of which might contain various optical elements or objects that are our specimens. At the ends of the paths, the waves will be out of phase because of the differing PLD's. Some sort of beam combiner is needed to bring the waves together so that they interfere. The interference, as we have learned, creates an intensity that is a function of the PLD. Some sort of device to measure intensity completes the setup.

### A FEW IMPORTANT POINTS

A particular aspect of interferometric measurement deserves great emphasis. The discussion so far has centered on the idea that we can measure the difference between two path lengths, and this, indeed, is one way that interferometry is used. But, there is another way that is even more useful. Suppose that we hold one of the paths constant and call it a reference path. Then, we induce a change in the second path, taking intensity measurements before and after the change. Subtraction of the post-change intensity from the pre-change intensity gives us the path length change in the second path. Such a procedure is very common in experimental mechanics measurements. In some instances, we need to account for changes in both paths in the course of an experiment.

Keep in mind that interferometry is a differential form of measurement, and that is one reason it is so versatile and useful.

The principles outlined here apply to other forms of waves. Interferometry can be performed with microwaves and at radio frequencies, for example.

### WHOLE-FIELD OBSERVATION

An oft-cited advantage of optical measurement techniques is that they yield a whole-field picture of the displacement or strain field. So far, we have considered only the case of two waves interfering, which implies that we obtain the PLD for only one small area of a specimen. The measurement is point-by-point. How can this idea be generalized to the entire field?

The answer is simple. We utilize a great many pairs of waves to interrogate all points in a specimen simultaneously using a multitude of interferometers. This is parallel processing of an advanced degree. At the conceptual level, we add to the generic interferometer a beam expanding device near the source to create a beam of, perhaps, parallel waves; or else we can use two beam expanders downstream from the beam splitter. The combiner joins the broad beams to create an intensity map of the field; this map shows the local intensities that are created by the local PLD's. The detector is a device, such as a camera, that can record and display this intensity map.

### ASSUMPTIONS

The index of refraction is actually a complex number. We have assumed that the materials involved are nonconductors, so we can ignore the imaginary part of the complex refractive index. This is not a serious restriction for most of our applications, but it has some implications when taking observations by reflection from metallic surfaces, as when interpreting Newton's rings.

### WHAT NEXT?

In the next installment, we will look at some applications of these ideas in basic forms of interferometry. After that, we will give some attention to the concepts involved in the phenomenon of diffraction.

### ACKNOWLEDGMENT

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*The components of all interferometric setups include:*

- light source
- beam splitter
- two optical paths
- beam combiner
- device to measure intensity

*There are two main ways that interferometric measurements can be accomplished:*

- measure directly the path length difference between two paths
- measure the change in one path length by holding one path constant while measuring the intensity change resulting from changes in the second path

*An advantage of optical methods is that we can perform interferometry over a broad field to obtain a map of local PLDs.*

*To extend interferometry to the whole field, we apply a multitude of interferometers operating in parallel. We modify the generic interferometer as follows:*

- add a beam expander near the source or separate beam expanders in each path
- use beam combiner that is broad enough to cover the field
- the detector is replaced by an imaging device such as a camera