OPTICAL METHODS Back to Basics *by Gary Cloud*

NEW DEPARTMENT

Optical Methods in Experimental Mechanics
Part 1: The Nature and Description of Light

INTRODUCTION

This article is the first in a pedagogical series on optical methods of measurement as used by practitioners in experimental mechanics. We start with the nature and description of light, progress to the two cornerstones of optical methods, interference and diffraction, and continue through the applications of these phenomena to measurement techniques such as holography and speckle interferometry. The main goals are utility, clarity, brevity, and accuracy.

WHAT IS LIGHT?

As we begin to study experimental methods that utilize light and optical components, this question is an obvious place to start.

The fundamental nature of light seems indefinable. We can say that light is a form of energy that is marked by two characteristics, namely:

- It moves—when it ceases to move, it is no longer light
- It carries a wealth of information

Beyond that, we are reduced to telling what light is by observing how it behaves and how it interacts with matter (e.g. tanning your skin, exposing a photo film) and with itself (e.g. interference). Further, we define some rather artificial but useful boundaries to distinguish light from similar but different forms of energy (electricity, heat). These distinctions are made primarily on the basis of interactions and behavior rather than on the basis of a fundamental definition.

Fortunately, we do not need to understand exactly what light energy is in order to use it and to describe and predict its creation, propagation, and interactions with materials.

HOW DO WE DESCRIBE LIGHT?

The fact that we do not totally understand the fundamental nature of light leads to a problem in describing its creation and behavior. We have two quite different experience-based systems, namely, quantum mechanics and electromagnetic wave theory. The application (photography, interferometry) dictates which system to use. The systems are not as differentiated as they seem; they actually are parts of a unified comprehensive theory called quantum electrodynamics. Yet, this bifurcation annoys tidy thinkers.

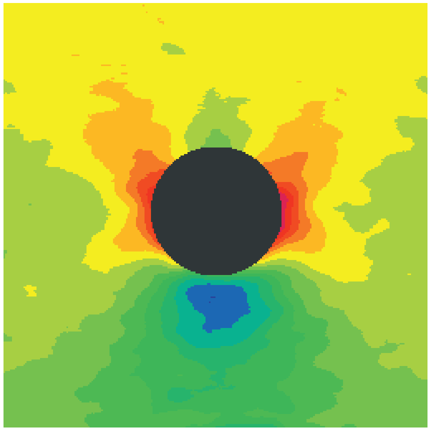
THE QUANTUM MODEL

The quantum model tells us that light consists of bundles of energy called photons. The generation and behavior of photons can be predicted through statistical mechanics. The photons have characteristics of both waves and particles. This approach is needed to explain various phenomena such as photoelectricity, lasers, and photography. We must rely on it in the detection and creation of light, both important in optical methods of measurement. But, we do not need to be experts in quantum mechanics in order to use a mercury lamp, a laser, or a television camera.

Editor's Note: *Please enjoy our new department,* Optical Methods: Back to Basics, *organized by ET Technical Editor Kristin Zimmerman, General Motors, and written by Prof. Gary Cloud of Michigan State University in East Lansing, MI. The series begins by introducing the nature and description of light and evolves, with each issue, into topics ranging from diffraction through to 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, is internationally known for his work in optical measurement methods and for his recently published book titled Optical Methods of Measurement and NDI.

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



False color strain map from phase-shifting speckle interferometry. Courtesy of F. Lanza, S. S. Hong, G. Cloud

Light is a form of energy that is marked by two characteristics:
- It moves—when it ceases to move, it is no longer light.
- It carries a wealth of information.

Apart from the question of exactly what light energy is, we need to describe and predict its:
- creation
- propagation
- interactions with materials

We have two experience-based systems to describe light:
- quantum mechanics
- electromagnetic wave theory

Quantum mechanics tells us that light consists of photons that have characteristics of both waves and particles. This approach facilitates explanation of phenomena such as:
- photoelectricity
- lasers
- photography

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ELECTROMAGNETIC WAVE THEORY

This model considers light to be energy in the form of electromagnetic waves. Proof of the wave nature of light was provided through the elegant experiment by Thomas Young in 1802, of which more will be said presently.

This theory is not totally adequate; it does not explain, for example, photoemission and photoresistivity. Most of the phenomena that are used by experimental mechanicians, including refraction, interference, and diffraction can be predicted and explained by wave theory.

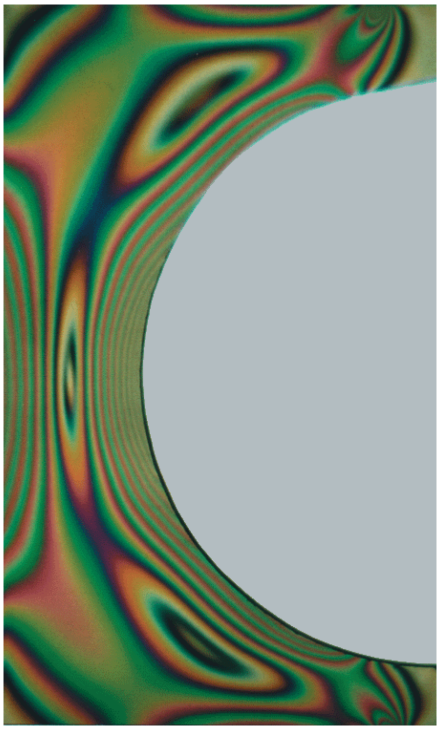
The behavior of the waves and their interactions with matter are conveniently described by Maxwell's equations. In order to understand the relationships between observables (e.g. light intensity) and mechanics response (e.g. displacement), we need to develop some facility with the equations describing waves.

Electromagnetic Theory teaches that light consists of energy in the form of electromagnetic waves. This approach explains:
- refraction
- interference
- diffraction

Electromagnetic theory is sufficient for most of our purposes.

Maxwell's Equations describe the behavior of electromagnetic waves by relating the:
- wave vectors
- field quantities
- material properties

For our applications, Maxwell's equations reduce to the wave equation.



Photoelasticity interferogram
Courtesy of Kenneth Singleton

MAXWELL'S EQUATIONS

James Clerk Maxwell (1831–1879) collected the work of several other scholars, particularly Faraday, added some inspired ideas of his own, and ended up with the systematic set of equations that are named after him.

The wave train of radiation is described in terms of two vectors that are perpendicular to each other and perpendicular to the axis of propagation of the wave. These wave vectors are: **E**, the electric vector, and **H**, the magnetic vector. If we know **E** and **H** as a function of time and position in the electromagnetic field, we have completely described the wave and its interactions with materials.

The relevant field quantities that may be seen as responses of materials are the electric displacement, the current density, and the magnetic induction. The material quantities in the field include the specific conductivity, the dielectric constant (related to index of refraction), the magnetic permeability, and the electric charge density.

Maxwell's equations relate the wave vectors, the field quantities, and the material properties. Fortunately, for most experimental mechanics applications, we do not need to be concerned with general solutions. A special case is sufficient.

THE WAVE EQUATION

In a nonconducting medium that is free of charge, Maxwell's equations reduce to the wave equation for vector **E** as a function of time and position.

The wave equation in one of several possible forms is:

$$\nabla^2\mathbf{E} = K\mu\,\frac{\partial^2\mathbf{E}}{\partial t^2}$$

where,

$$\nabla^2 = \frac{\partial^2}{\partial x^2}\,\mathbf{i} + \frac{\partial^2}{\partial y^2}\,\mathbf{j} + \frac{\partial^2}{\partial z^2}\,\mathbf{k}$$

K = dielectric coefficient of the medium
μ = magnetic permeability
$K\mu = 1/v^2$
v = speed of propagation of the wave.

This equation shows how, for the restrictions accepted, the electric vector, the material properties, the wave speed, and spatial coordinates are related. For most of our work, we need not consider any general solutions to the wave equation. We need only the simplest solution.

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THE HARMONIC PLANE WAVE

A simple solution to the wave equation, the harmonic plane wave traveling along the z-axis, allows us to do most of the calculations required in basic experimental mechanics. It is,

$$\mathbf{E} = \mathbf{A} \cos\left[\frac{2\pi}{\lambda}(z - vt)\right]$$

where,

$\mathbf{A}$ = a vector giving the amplitude and plane of the wave
λ = the wave length
v = the wave velocity.

There are two useful ways to visualize the wave. If we could take a snapshot at some fixed time, the wave would look like a cosine plot along the z-axis. Alternatively, we might sample the amplitude of the wave at some fixed "z" over a period of time. The amplitude plotted as a function of time would also be a cosine graph. These experiments are difficult to do because the wavelengths of light are very small—on the order of a half a micrometer, and the wave frequencies are large—in the vicinity of 10^{14} Hz. Recall that, in the sensory domain, wavelength and frequency appear as color.

So, the basic wave function contains in one simple expression all the important data about the wave, including its strength, polarization, wavelength, direction, and speed.

As we get into calculations for more complicated processes such as holography, it will be necessary to generalize this equation by doing the following:

- allowing it to travel along an arbitrary axis instead of just the z-direction
- changing it to an exponential form
- realizing that we need use only the complex amplitude.

The simplest solution to the wave equation is sufficient for our purposes.

It is a harmonic plane wave traveling along an axis.

The important wave data are:
- strength
- polarization
- wavelength
- direction
- speed

WHERE DO WE GO FROM HERE?

In the next segment, we will see what happens when two simple waves are mixed together in the process known as interference. Interference is one of two cornerstones in the study of optical methods of measurement. We are then led to the broad application area known as interferometry. Then, we will study what happens when light passes through an aperture in the process known as diffraction. ■

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