OPTICAL METHODS Back to Basics *by Gary Cloud*

Optical Methods in Experimental Mechanics

Part 9: The Diffraction Problem

REVIEW AND PURPOSE

The first eight installments in this series have dealt with the nature of light and the first of the two cornerstones of optical methods of measurement, namely the interference of light waves. There is much more to be said about types and applications of interferometry, and, indeed, we will return to those subjects presently.

It is time to augment our understanding of the behavior of light and to expand our arsenal of tools through study of the diffraction of light waves, the second of the two cornerstones. This segment provides some observations about our physical world that motivate study of the problem, mentions some potential applications, gives some background of the long history of the solution, and defines the problem in its simplest form.

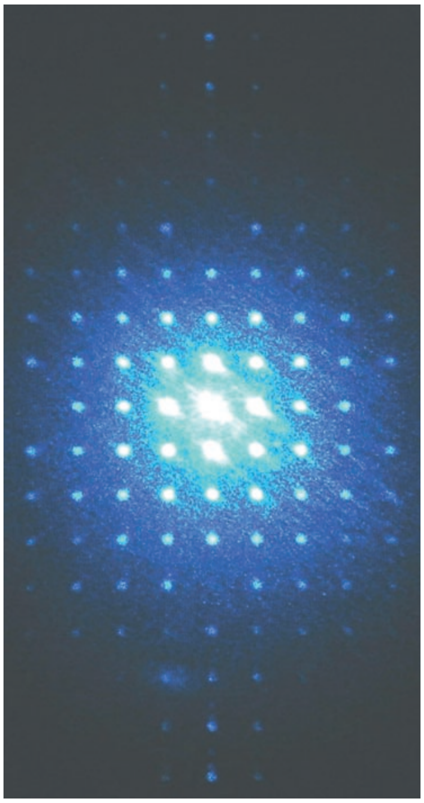
EXAMPLES OF DIFFRACTION

Here is a series of simple experiments that illustrate various aspects of diffraction of light at an aperture and also give some idea of its ubiquitous presence in our activities.

First, project light through a sharp-edged hole (aperture) in a piece of cardboard or shim stock (aperture plate). An ordinary lamp, a flashlight, or, even better, the sun can be used as the source; but a practical alternative is to use an inexpensive laser pointer. A piece of cellophane mending tape stuck to the end of the pointer will serve to expand the beam to cover the hole if needed. What is observed on a viewing screen that is placed downstream from the hole? Lifelong experience suggests that you should see a simple shadow of the aperture plate; that is, the viewing screen will be dark except where it is lit by the energy coming through the hole. Close observation shows something more complex. The edges of the shadow will be fuzzy. If using a very small light source, the sun, or a laser for illumination, you might even be able to see interference fringes at the edge of the shadow.

Investigate further by continuing the experiment with consecutively smaller apertures. You will notice that the fringes near the edge of the shadow become stronger. If the aperture is made really small, approaching a pinhole, the bright area on the screen will be larger than the aperture, and you might notice some well-defined concentric rings in the pattern. As you shrink the aperture ever smaller, the bright patch on the screen becomes ever larger, suggesting an inverse relationship that seems totally contrary to our experience and expectation.

Now, modify the aperture so that it contains some simple but ordered intelligence. One way of doing this is to repeat Young's experiment, as was done for Part 6 of this series of articles. The aperture is just a pair of tiny holes close together. One



Portion of diffraction pattern from photographic replica of a crossed bar-space grating (grid) having spatial frequency 1000 lines / in. Argon laser, no enhancement. Orders visible to eye range from −15 to +15 in both directions. Digital photo by Gary Cloud, Sept. 2003.

Diffraction is the second cornerstone of optical methods of measurement.

Examples of diffraction of light waves are all around us, and may also be observed through simple experiments.

Illuminate a hole (aperture) in a plate and examine the shadow on a screen. The shadow cast by the sharp edge will be found to be fuzzy and might exhibit interference fringes

If the aperture is made small,
- *the illuminated patch on the screen will be larger than the aperture*
- *clear fringes might be observed near the shadow edge*
- *we note an inverse relation between aperture size and expansion of the beam.*

Editor's Note: Optical Methods: Back to Basics, *is organized by ET Senior Technical Editor, Kristin Zimmerman, General Motors, and written by Prof. Gary Cloud 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 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 noted otherwise, graphics in this series were created by the author.*

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.

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sees on the viewing screen a large illuminated patch that is modulated by a system of parallel interference fringes. As was mentioned, the explanation based on Huygens' construction requires a great leap of faith. A better explanation is developed from diffraction theory.

Modify the setup again by passing the laser beam through a very fine sieve or mesh. For best results, the mesh density should be on the order of at least 100 threads or lines per inch. Fine fabric such as hosiery (not the stretch kind) or other sheer nylon, preferably black, can be used, in which case the viewing screen (maybe the wall) should be a few meters distant. The screen exhibits an array of bright dots. The geometry of the dot pattern depends on the way in which the mesh or fabric is woven. The dot spacing increases as the thread spacing is decreased, which is contrary to uninformed expectation.

The pattern on the viewing screen depends on the type of intelligence (signal) in the aperture.
- *If the intelligence consists of two small apertures close together, then we observe Young's fringes.*
- *If a fine mesh is placed in the aperture, we observe an ordered array of bright dots on the screen.*
- *The dot spacing is inversely related to the distance between the apertures or the threads of the mesh.*

Change the experiment again by allowing the beam that falls on the aperture to carry some sort of information. The difference is that the beam carries the data and the aperture is just a hole, rather than having a uniform beam illuminating intelligence in the aperture. For example, you might use the light that is scattered from a distant object. If the aperture is pinhole-small (about 0.4 mm), an inverted image of the object will be observed on the screen. Light intensity will be very low, so the screen must be in a relatively dark place. This phenomenon was discovered at least 1000 years ago and was described in the notebook of Leonardo da Vinci. It has long been used to safely observe solar eclipses. A device based on this discovery, called the "camera obscura" (dark room), was used by renaissance artists. Nowdays it is called the pinhole camera and is used by children for simple photography. How can a tiny hole function as an imaging lens?

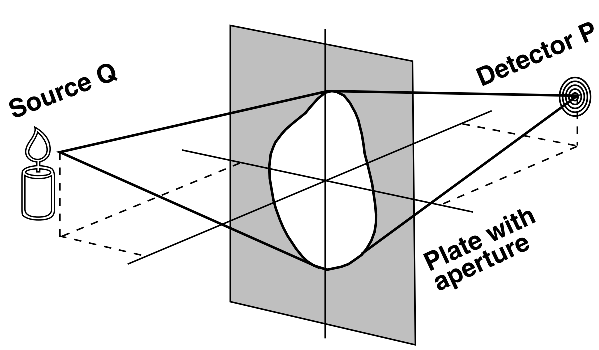
The pattern on the viewing screen also depends on intelligence carried by the beam. If the beam comes from an illuminated object and if the aperture is quite small, then,
- *an image of the object appears on the screen,*
- *we have created a "camera obscura" or "pinhole camera."*

This example requires a little more equipment. Set up a lens to image a backlit window screen onto a ground glass or just a piece of white cardboard. Place an iris diaphragm near the lens to control its aperture. Better, set up a view camera or a single lens reflex if you have one. Use a magnifier to examine the image of the mesh as you decrease the aperture of the imaging lens. At some small aperture setting (large f-number), you will find that the mesh image loses contrast, and it eventually disappears. The implication is that decreasing the aperture diminishes the ability of the lens to transmit information that has high spatial frequencies (fine detail); that is, a lens is a tunable low-bandpass filter. Think about the conventional wisdom that instructs us to use extremely small apertures for the sharpest pictures. Are we properly instructed?

The ability of a camera lens to render fine detail depends on the size of the aperture.
- *Relatively large apertures allow reproduction of finest detail.*
- *Tiny apertures limit the detail that can be reproduced.*
- *This behavior is contrary to conventional wisdom in photography.*
- *A lens appears to be a tunable low-bandpass filter.*
- *Lens aberrations modify these phenomena.*

THE DIFFRACTION PROBLEM

Experiments and observations such as those mentioned above led to the formulation of a classic problem in mathematical physics. Consider the following sketch:



The "diffraction problem" is stated as follows. Light from a source illuminates an aperture in an opaque plate. Describe the light received at some point downstream from the aperture.

Light emitted by a source at location Q falls on an opaque plate containing some kind of aperture (hole). The aperture may or may not contain intelligence such

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as a transparency or an optical element such as a lens. The task is to describe the light field that will be received at point P downstream from the aperture.

This deceptively simple problem is of fundamental importance in optics, including electron microscopy. It provides understanding of the formation of images by optical components, and it leads to ways of specifying and measuring the performance of optical systems. Diffraction theory allows us to utilize certain optical elements as Fourier transforming devices, thereby giving us the ability to perform whole-field optical processing of spatial signals (pictures) to modify content and improve signal/noise ratio. The results are critical to experimental mechanicians who seek to thoroughly understand geometric moire, moire interferometry, speckle interferometry, holo-interferometry, and so on.

HISTORY OF SOLUTION

The diffraction problem is much more complex than it might seem, and it has not been solved in general form. The oldest solution, mentioned in Part 6, rested on the assumption by Huygens in 1678 that the illuminated aperture can be replaced by an array of point sources. This equivalent problem was solved correctly by Fresnel and by Fraunhoffer in the early 1800's, although not all observed phenomena were explained. The Huygens-Fresnel-Fraunhoffer approach is still useful because it provides an easy way to visualize diffraction phenomena.

Rigorous solution of the diffraction problem was accomplished in 1882 by Kirchhoff, who treated it as a boundary value problem and incorporated several severe simplifying assumptions. Kottler and Sommerfield used mathematical theory developed by Rayleigh to refine, extend, and correct Kirchhoff's elegant analysis. These solutions incorporated several of the ideas that were developed in the earlier era by Fresnel and Fraunhoffer.

THE TASK

Before proceeding further, we must develop a way to deal with light waves that is more compact and less unwieldy than the trigonometric approach used so far in these articles. Then, the outline of the solution will be presented, omitting mathematical development and emphasizing physical meaning. We are then in position to explore and utilize the elegantly simple result. ■

Diffraction theory is fundamental in optics, electron microscopy, experimental mechanics, and other fields because it leads to:
- *understanding of image formation of optical systems,*
- *ways to specify and test optical devices,*
- *conception of apertures and lenses as Fourier transformers,*
- *methods to take advantage of frequency response of systems,*
- *ability to perform optical whole-field processing to modify frequency content of pictures.*

For the experimental mechanician, diffraction theory is important in:
- *geometric moire*
- *moire interferometry*
- *holography and holointerferometry*
- *speckle interferometry*
- *speckle photography*
- *shearography*
- *other methods*

The diffraction problem:
- *is more difficult than it appears to be,*
- *has not been solved in generality,*
- *was formulated in 1678 by Huygens, who incorporated a major simplifying assumption,*
- *was solved by Fresnel and Fraunhoffer in the form established by Huygens,*
- *was reformulated and solved as a boundary value problem by Kirchhoff in 1882,*
- *was later solved with more rigor by Kottler, Sommerfield, and others.*

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