Optical Methods in Experimental Mechanics

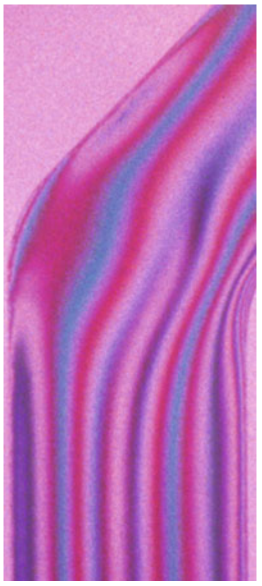
Part 7: Colored Interferometry Fringes

PURPOSE

The topic of classical interferometries is not yet exhausted, but this is a good time to digress a bit and answer questions as to why interference fringe patterns are sometimes monochrome and sometimes brilliantly colored, and also to explore the uses of these patterns.

CONTEXT

Suppose you are demonstrating some interferometric process, such as photoelasticity, using an overhead projector, and you are projecting the fringe pattern on a screen. Experience suggests that the audience will be delighted by the rippling flow of brightly colored interference fringes, and some might be so impressed that they decide to follow a career in experimental mechanics. Later in the demonstration you might use a laser to show another type of interferometry, and the fringes will be monochromatic; or you might show a black and white fringe picture that you have used for precise quantitative analysis. The audience will likely ask why some patterns are colored and some are monochrome, and they might wonder why you waste time with the monochromatic patterns when you can create amusing colored ones.



Detail from light-field photoelastic interferometry fringe pattern obtained using simultaneous illumination from two laser sources: Argon at 488 nm (turquoise) and Helium-Neon at 633 nm (red). The granular appearance is caused by laser speckle. Photo by Gary Cloud, March 2003.

A THOUGHT EXPERIMENT

To help us understand the formation of colored fringes, consider a thought experiment. We set up a system that is similar to the generic interferometer that was discussed in Part 3 of this series. Imagine that we can control the path length difference (PLD). We use for illumination a single wavelength of light such as from a laser. Suppose that we begin by using a laser that emits blue light at a wavelength of 440 nm. We connect the detector in the interferometer to a plotter that displays intensity as a function of the PLD. We know from our study of this problem (see Part 2) that we will obtain a plot of intensity versus PLD, such as is shown by the blue trace in the bottom portion of Fig. 1. Whenever the PLD is a multiple of the 440 nm wavelength, the intensity will be zero.

Now, suppose we exchange the blue laser for one that emits red light at 660 nm wavelength. The experiment is repeated. The trace of intensity versus PLD will match the red trace in the figure, with zero intensity whenever the PLD is a multiple of 660 nm.

Suppose, finally, that we put both lasers into the setup and do the measurements again with simultaneous red and blue illumination. The plotter will display the sum of both the traces obtained when the lasers were used separately. This resultant intensity trace is not reproduced in the figure, but it is easy to visualize qualitatively.

- *Why do we see a brilliant pattern of colored interference fringes in some experiments?*
- *What do these colored patterns mean?*
- *What are their uses?*

We create a thought experiment:

- *involving some type of interferometer*
- *a choice of red or blue illumination is provided*
- *the PLD is controllable*
- *the intensity detector output is plotted as a function of PLD for each wavelength.*

Editor's Note: Optical Methods: Back to Basics, *is 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 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.

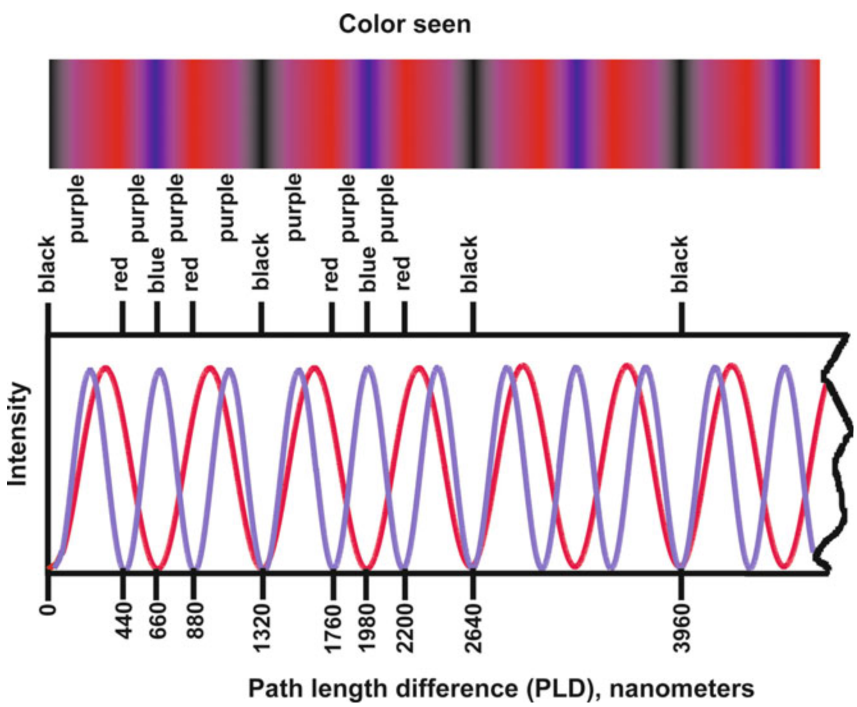


Fig. 1

More illuminating is to imagine that we replace the intensity detector with a sensor that responds to color, such as a color camera or our eye. This sensor will yield, at each PLD, the color that is created by adding the blue and red components that were recorded individually at that PLD. For example, at a PLD of around 300 nm, approximately equal intensities of blue and red are passed through, and they add to create purple or magenta, which is the color that is perceived. For a PLD of around 700 nm, most of the red is eliminated by interference, so we are left with a lot of blue, meaning that we perceive a blue with a slight purple cast.

The rainbow-like color bar at the top of the figure shows the resultant color that is perceived as the PLD is increased when the two wavelengths are used simultaneously, as suggested above. Here, the total intensities are not correct, but the hue is pretty close to true value. Observe first that the sequence of colors is not all that simple, even though we are using only two wavelengths that were purposely chosen to keep the color pattern as tidy as possible (660 nm = 1.5 × 440 nm).

Let us explain the different colors observed by visualizing the superimposition of the two intensity plots and remembering that we are dealing with light and not pigments.

- At zero PLD, there is no light, so we start from black.
- As the PLD increases from zero to about 220 nm, approximately equal amounts of red and blue are mixed, so we see a slowly changing purple that becomes more intense as the amplitudes increase.
- Beyond 220 nm PLD, the blue begins to drop off while red stays strong, so the purple fades quickly into red.
- At 440 nm, the blue is canceled by destructive interference, so only red remains.
- Between 440 and 660 nm, the blue increases while red drops off, so we have a short band of rapidly changing purple that is getting more blue.
- At 660 nm, the red is canceled, so we perceive pure blue.
- Between 660 nm and 1320 nm the sequence just described is reversed.
- At 1320 nm = 2 × 660 nm = 3 × 440 nm, both red and blue undergo total destructive interference, so we finally get back to black.

The detector output shows that the intensities for red and blue oscillate between zero and maximum at different rates, depending on the wavelength used for illumination.

The experiment is then performed with the following changes:

- *combined red and blue illumination is provided*
- *a color sensor is substituted for the intensity detector.*

The sensor yields a resultant color that is created by the mixture of red and blue components remaining at each PLD.

If color is plotted with increasing PLD we will see a sort of color spectrum that is fairly complex even though only two wavelengths were used in the experiment.

As PLD increases from 0 to 1320 nm, the sequence of colors is:

- *black slowly shading through purple to red*
- *red shading quickly through purple to blue*
- *blue shading quickly through purple to red*
- *red shading slowly through purple to black, where minima of both blue and red are reached*
- *the color cycle repeats for each successive segment of 1320 nm PLD.*
- *for each black-to-black segment, we pass through one stage of pure blue, two stages of pure red, and 4 stages of purple shades.*

- Between 1320 nm and 2640 nm PLD, the whole sequence of colors is repeated.
- And so on.

The photograph appearing with this article suggests that these predictions are valid. The color sequence in the experiment is not quite the same because the two wavelengths used were different from those used in the thought experiment.

An obvious question is, "For any given PLD, what is the fringe order?" No truly meaningful answer to this question presents itself. At PLD = 3960 nm, we have migrated through 3 cycles of pure blue, 6 cycles of pure red, 4 cycles of black (counting the zero), and no less than 12 cycles of purple. Unless you name a wavelength or color, the concept of fringe counting has no meaning. Furthermore, notice that the cycles of certain colors (purple in this case) are not necessarily evenly spaced. This is one reason why colored fringe patterns, while very nice to look at and impress managers with, have not often been used for quantitative analysis.

Our usual concept of fringe counting does not apply to colored fringe patterns.
- *we must count in terms of the cycles of a certain color*
- *for some colors, the cycles are not evenly spaced.*

Imagine doing the thought experiment with some form of interferometry that creates a large field where the PLD varies continuously over the field. The experiment can involve the oblique intersection of two beams (Part 4 of this series), Newton's fringes (Part 5), Young's fringes (Part 6), photoelasticity (not discussed yet), or any one of several other possibilities. The PLD at each point in the field will give rise to a specific color according to the rules described above. Further, if the PLD varies smoothly over the field, then the colors will also vary smoothly, hence, a "colored fringe" pattern.

If more than one wavelength of illumination is used in a whole-field interferometer, then we observe a field of colored fringes.

An immense question remains. What happens if more than two wavelengths are used, or even a continuous spectrum? Repeating the thought experiment with 3 separate wavelengths is entertaining, instructive, and time-consuming. For four or more wavelengths, the problem gets out of hand, partly because you run out of wavelengths in the narrow visible spectrum that have nice mathematical proportions. Better to go to the lab with color filters or spectral sources, a photoelasticity model, and some means of judging colors.

If several wavelengths are used, predicting the resultant colors over a range of PLD's becomes quite difficult.

With continuous spectrum illumination you will see the complement of whatever colors are canceled by destructive interference. For PLD's beyond the first cycle, the problem gets very tricky. For example, the third cancellation of blue matches the second cancellation of red, as we found in our experiment, and you have left white light that has both red and blue removed, with the remaining colors mixed in uneven proportions. Black will not be seen again. The sequence of colors is no longer cyclic as it was in our thought experiment, and the colors lose saturation, tending to pastel shades and eventually to white.

For continuous spectrum illumination in an interferometer:
- *the fringe colors are the complement of whatever colors destructively interfere at any PLD*
- *for PLD's beyond the first cycle, predicting and interpreting the color sequence is difficult*
- *the color sequence is no longer repetitive or periodic*
- *for large PLD's the various colors combine in ways that cause the saturation to diminish, producing pastels that eventually tend to white—no colors.*

Various investigators have published charts of resultant color versus PLD for ideal white-light illumination (sunlight or equivalent). One such chart appears in *Spannungsoptik* by G. Mesmer, Springer-Verlag, 1939; this chart is reproduced in *Optical Methods of Engineering Analysis* by Gary Cloud, Cambridge University Press, 1995 and 1998, p98. The catch is that it is very difficult to reproduce sunlight. The colors observed are dependent on the color spectrum in the actual illuminating beam, the transmittance spectra for the optical components and the specimen, and also the precision with which one is able to record or judge color, itself a difficult task. These difficulties are the second reason why colored fringes are not usually used for quantitative measurement.

Fringe colors depend on:
- *the spectral content of the source*
- *the transmittance spectra of the optical components and specimen*
- *the color rendition or accuracy of the observing device*

The third difficulty with color methods results from the way refractive index varies with wavelength, a phenomenon called dispersion.

That said, colored fringes do have important uses. For one thing, the color sequence is very useful in establishing the direction of the gradient of fringe orders in whole-field work, thereby helping solve the vexing problem of fringe counting. Interpolation between whole-order fringes can also be facilitated by using colors.

Colored interferometric fringes:
- *are not often used for quantitative analysis by themselves*
- *help us in fringe counting by showing the fringe gradient*
- *help with interpolation between fringes.*

In recent years, the advent of color video cameras and digital processing has led to a resurgence of interest in the use of colored fringes in interferometry, especially in what is often called RGB photoelasticity. Such systems can be calibrated to account for the color balance in the light source and sensors, eliminate the effects of color absorption in the specimen, and also eliminate errors caused by dispersion. These methods are now practical for obtaining accurate results, especially when fringe orders are small, from colored interferometric patterns that once were used primarily to impress layfolk and add cosmetic appeal to engineering reports.

Colored fringe information is now put to good effect in electronic forms of interferometry including, for example, RGB photoelasticity.

In a way, the story of colored fringes has come full circle. It is likely that the earliest fringe patterns observed by Thomas Young and others were created with near-white light (candles, arc lamps). Then, spectral sources became available; and, given the problems in judging color and so on, most serious interferometric measurements were done with monochromatic light. Color video cameras and digital processing make it possible to analyze accurately the spectral content of light; and, so, we return to the use of broadband illumination and colored fringes for accurate analysis. ■